

**TECHNOLOGY OPPORTUNITIES TO REDUCE
U.S. GREENHOUSE GAS EMISSIONS**

**Appendix B
Technology Pathways Characterization
(Working Document)**

October 1997

**Prepared by
National Laboratory Directors
for the
U.S. Department of Energy**

**On the World Wide Web:
http://www.ornl.gov/climate_change**

INTRODUCTION AND METHODOLOGY

Overview

A major objective of this study was to compile information on the potential of a wide range of energy-related technologies to reduce carbon dioxide emissions through additional RD&D. This was done by identifying a large team of individuals with relevant energy technology expertise, organizing them into 11 working groups to address 11 technology areas, and providing them with guidance for developing the desired information. The 11 technology areas included 9 categories of technology pathways, plus cross-cutting technologies and related areas of basic research.

Each working group was responsible for identifying the individual technology pathways appropriate to their technology, drafting the text for Chapter 2 of the main report, and preparing the two-pagers contained in this appendix. In order to complete all of these tasks, the working groups developed a large amount of information about the technologies in their area in the context of the 30-year timeframe that underlies this study. This information was critical in estimating which technologies provided the best opportunities for reducing GHG emissions in the U.S.

In addition to discussing the technical aspects of the best technological pathways for reducing GHGs, the working groups sought to develop general estimates of the potential costs and benefits of each technology pathway. It is important to note that the cost-benefit estimates are only approximate, relative indicators of what might be achievable if the technological goals are met.

The working groups relied upon Delphi Method principles to reach their conclusions about the technology pathways. Conditions and assumptions not defined in this Appendix were based on a consensus of the working group members.

An important part of the overall study methodology took the form of a “consistency scrubbing” exercise. A small group carefully reviewed all of the technology pathways for consistency and credibility, and then interviewed working group representatives to ensure that the technology pathway information had a firm technical basis and was developed through a sound analytic process. In addition, the small group reviewed how the carbon emission reduction estimates and the risk factor scores were developed to ensure that all the working groups followed the agreed upon guidelines.

Technology Pathway Two-Pagers

This appendix contains two-page descriptions of 47 climate change technology pathways. The appendix is not a comprehensive inventory of every possible technology that could reduce GHG emissions. Rather, it focuses on 47 pathways that were judged by the working groups to be sufficiently promising to warrant serious consideration. The attributes of the technologies comprising each pathway area were assessed independently by the working group responsible for that area. Thus further analysis would be required to prioritize all 47 technology pathways based on their likely costs and benefits.

Each two-page pathway provides a technology description (covering system concepts, representative technologies, and the technology’s current status), describes current research, development, and demonstration (RD&D) activities (including RD&D goals and challenges), and presents one or more recent successes. Each pathway also discusses the prospects for commercialization and deployment of the technology and describes potential benefits and costs (including carbon reductions, market impacts,

nonenergy benefits and costs, and RD&D expenditures). Finally, six types of risk factors are assessed, and study recommendations in the form of key federal actions are made.

The descriptive text and the numerical estimates presented in these pathways are based on the judgment of the working groups formed from the 11 national laboratories participating in this effort and in some cases, in collaboration with experts from other organizations across the country. Analysis supports some of the numerical estimates provided in the two-pagers. In other cases, the estimates were the best estimates of experts based on available information. Standardized protocols and assumptions were used by each working group to promote consistency in defining terms and in estimating values. As an additional mechanism for increasing overall consistency among the technology pathways, a small focus group discussed drafts of each pathway with the working group that drafted the two-pager. Although this was a lengthy and time-consuming process, it resulted in numerous clarifications and improvements to the pathways, including their numerical estimates. Finally, numerous DOE program managers reviewed preliminary versions of the report, as well as the technology pathways.

A discussion of the guidance provided to the teams and other relevant issues regarding assumptions and interpretation of the pathways is presented by topic.

Estimation of Carbon Emission Reductions

The estimated carbon emission reduction of each pathway is the portion of the cost-effective potential that could reasonably be expected to result from an enhanced RD&D effort, with no significant changes to government policies or deployment programs. These reductions are an estimate of reasonable expectations, not inherent capacity. Estimates of carbon reduction are provided in terms of millions of metric tons of carbon (MtC or 10^{12} gC) that could be displaced annually by the technology, above and beyond the reference case forecast, for each of the decades ending in the years 2010, 2020, and 2030.

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. The factors that the teams considered include the following:

- 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
- environmental and health risks associated with the technology
- public perception and acceptance risks
- characteristics of competing technologies

Reference Case. U.S. CO₂ emissions are projected by the U.S. DOE Energy Information Administration (EIA) to increase at a rate of 1.2% per year under a “business-as-usual” scenario. This scenario assumes that some efficiency and process improvements will offset what would otherwise be a larger rate of CO₂ 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, CO₂ 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 Table B.1 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.

Table B.1. U.S. carbon dioxide emissions by end-use sector
(in MtC per year)

	Emissions				Change from 1990		
	1995	3020	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

^aThe 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 CO₂ are not included.

Federal RD&D Efforts. The federal government has a substantial program in energy RD&D, designed to support the broad national goals of energy security and environmental quality. Although the existing energy RD&D programs were not designed specifically to reduce carbon emissions, they also will have significant benefits for mitigating climate change. The carbon emission reduction estimates presented in Appendix B and the main report are based on the assumption of an enhanced federal RD&D program. Because the current federal RD&D effort is taken into account in the reference case, the pathway

estimates of carbon reductions are incremental to the reductions that would result from a continuation of current levels of federal RD&D funding. The estimated RD&D support needed to achieve these incremental carbon reductions is based on the judgment of the working groups from the 11 participating national laboratories (and in some cases in collaboration with experts from other organizations across the country).

The RD&D budget estimates are expressed in 1997 dollars. R&D priorities and any budget decisions should be based on more detailed planning and analysis than was possible during development of this report. Initiation of that analysis and planning is one of this report's primary recommendations.

Private-sector Efforts. Federally funded RD&D is certainly not the only effort that will be needed to develop and demonstrate the technologies described in these pathways. Private-sector collaboration is a major element of many federal RD&D programs and will need to continue and expand along with the federal commitment to enable the nation to achieve the advances described in this report. Private-sector expenditures are not included in the estimates of the required federal RD&D expenditures.

Federal Policies. The technology pathways—and the main report—assume a continuation of existing federal programs and policies. The estimates do not presume the creation of any new incentives such as investment tax credits, a carbon charge, or a domestic or international CO₂ trading system.

Non-additivity. The effects of the market success of one technology pathway on the market success of another technology pathway were generally considered within one particular technology area, such as within nuclear energy or within buildings efficiency. The effects of competition among technology areas could not be fully evaluated; therefore, carbon reduction estimates from different technology areas (such as nuclear and buildings efficiency) cannot simply be summed. The problem is that the technology areas compete and interact with each other. For instance, if enhanced natural gas production should cause electricity generation to shift from coal to gas, new coal technologies would generate fewer carbon savings. If carbon emissions from the generation of electricity were reduced, the carbon reduction potential from saving electricity in the buildings and industrial sectors would also decline.

Secondary Demand Effects. The estimates of carbon reduction potential do not reflect possible changes in demand for energy services resulting from the introduction of the technology. Improved energy efficiency and more competitive low-carbon energy sources suggest lower energy prices and costs of energy services. These would likely increase demand for energy services and “take back” some portion of the reported savings. Should the demand for energy services and the energy cost of these services change, so would the competitiveness of the technologies explored. These secondary demand effects are not incorporated in the carbon reduction potentials.

Restructuring. The carbon reduction estimates 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.

Description of Risk Factors

The technology pathways consider six risk factors that are labeled: “technical,” “commercial,” “ecological,” “human health,” “economic,” and “regulatory.” These risk factors are defined as follows.

Technical Risk: Refers to the risk that the federal R&D dollars will not result in the commercialization of the technology for cost or performance reasons. Technologies that require only incremental innovation generally have lower technical risk than technologies that require a major breakthrough. Technical risk also generally increases as the number and complexity of associated technologies increase. Thus a technology that is a stand-alone product tends to have lower risk than a technology with many components that need to be developed. In addition, technical risk is negatively correlated with the availability of necessary resources. Therefore, a technology that can be developed with readily available resources (i.e., equipment and/or skills) involves less technical risk than a technology that requires more demanding types of resources. This risk factor takes into account the probability of achieving the cost reductions necessary for a technology to be cost-competitive.

Commercial Risk: Reflects the magnitude and likelihood of commercial vulnerabilities that could hinder successful deployment. Examples of high commercial risk include the need to make massive infrastructure investments or the need to establish a new system of operations and maintenance support for a product. Thus the more changes that are needed in the infrastructure and the more training that will be required by the operations and maintenance providers, the higher the commercial risk. Commercial risk also depends upon the size of the resource base relative to the technology's requirements: limited resources will constrain commercial deployment, and risks are especially high when a technology is strongly dependent on foreign sources.

Ecological Risk: Refers to the probability that a technology could cause significant effects on nonhuman species and aquatic and terrestrial ecosystems. Ecological risk is calibrated in comparison with the new technology's competitors and is generally positively correlated with the severity of the possible effects and their spatial and temporal extent. Examples of high severity include the release of highly toxic byproducts from a technology or the severe modification of habitats as a result of land conversion or water depletion. Spatial extent includes land area or aquatic system length or volume, normalized to the importance of the ecological resource. The temporal extent includes both the time for which the ecological resources would be affected and the time to recovery given the persistence of contaminants and the rate of recovery and adaptation of the affected ecosystem.

Human Health Risk: Refers to the probability of adverse human health consequences as a result of the commercialization and deployment of the technology. As in the case for estimating ecological risk, human health risk is calibrated in comparison to the new technology's competitors. Thus the human health risk of high-efficiency coal-based power generation is considered relative to alternative sources of electricity, including conventional coal generation, natural gas systems, nuclear power, and electricity from renewable resources. Occupational hazards associated with the manufacture of a technology are included in this risk factor.

Economic Risk: Refers to the probability that a technology could be rejected because competing technologies are preferred by consumers. Economic risk is lower when consumers do not have to change their behavior when using, purchasing, or servicing the product. In addition, economic risk is reduced when the new technology's costs compare favorably with the costs of the product that would be displaced, so that the economic decision makers don't need to change their investment behavior. Public preferences can be strongly supportive (as with energy-efficient industrial technologies that also reduce pollution), or they may impede implementation of a technology, leading to economic penalties.

Regulatory Risk: Refers to the probability that current or future U.S. regulations will prevent the technology from meeting its commercialization and deployment targets. For existing technologies, onerous regulations would increase regulatory risk. For technologies that have not yet been

commercialized, the absence of regulations such as codes and standards may suggest a high regulatory risk.

The study teams assessed the risk factors for each pathway using a 10-point scale. Values on this scale should be interpreted as follows:

- Scores of 9–10 are considered to be so high as to render a technology infeasible over the next half century. All of the pathways in this report are considered feasible during this time frame, so none have been rated with risk scores above 8.
- A score of 1 is considered to be very close to no risk at all. Since some uncertainty is inherent in all research, few of the pathways received this score in any risk category.
- Scores of 2–3 are considered low risk; scores of 4–6 are considered moderate risk; and scores of 7–8 are considered high risk.

The scores apply to the pathways over the 30-year range of the study, reflecting the results of strongly supported RD&D but assuming today's policies (consistent with the rest of the report). The scores represent the best judgments of the national laboratory participants. "N/A" or "not available" was assigned in cases where it was not possible to anticipate what the risk levels might be in the future.

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Energy-Efficient Technologies

1. Buildings

1.1 Equipment and Appliances

1.2 Building Envelope

1.3 Intelligent Building Systems

1.1 EQUIPMENT AND APPLIANCES

Technology Description
<p>All energy use in buildings depends on equipment to transform fuel or electricity into end-use services such as delivered heat or cooling, light, fresh air, vertical transport, cleaning of clothes or dishes, and information processing. There are energy-saving opportunities within individual pieces of equipment—as well as at the system level—through proper sizing, reduced distribution and standby losses, heat recovery and storage, and optimal control. Another promising opportunity lies in multifunction devices ranging from heat pumps that provide both refrigeration and hot water, to an office appliance that serves as a networked printer, copier, scanner, and paperless fax machine.</p> <p>System Concepts</p> <ul style="list-style-type: none"> • Major categories of end-use equipment include heating, cooling, and hot water; ventilation and thermal distribution; lighting; home appliances; miscellaneous (process equipment and consumer products); and on-site energy and power. • Key components vary by type of equipment, but some cross-cutting opportunities for efficiency are improved materials and applications, efficient low-emissions combustion and heat transfer, advanced refrigerants and cycles, electrodeless and solid-state lighting, smart sensors and controls, improved small-power supplies, variable-capacity systems, reduction of thermal standby losses and leaking electricity, and modular fuel cell-based micro-cogeneration. <p>Representative Technologies</p> <ul style="list-style-type: none"> • Residential gas-fired absorption heat pumps, desiccant pre-conditioners for treating ventilation air, proton exchange membrane (PEM) fuel cells, horizontal axis clothes washers, and low-power sulfur lamps. <p>Technology Status/Applications</p> <ul style="list-style-type: none"> • Technology improvements over the past 20 years—through quality engineering, new materials, and better controls—have improved efficiencies in many types of equipment by 15 to 20%. Electronic equipment is an outlier with order-of-magnitude efficiency gains, at the microchip level, every 2 to 3 years. • Continued technical innovation, spurred by government/industry co-investment in R&D and effective, sustained market-pull policies, could at least match and potentially double these prior efficiency gains over the next 20 years.
Current Research, Development, and Demonstration
<p>RD&D Goals</p> <ul style="list-style-type: none"> • By 2002, commercial introduction of full-size refrigerator-freezers that use as little power as a 40-W light bulb. • By 2010, heat pumps for residential and small commercial applications with 40% improvement over conventional gas furnaces. • By 2010, reduced standby losses, improved heat pump water heating, and application of heat recovery techniques reduce energy use for domestic water heating by 60% over conventional devices. • By 2010, commercial introduction of hybrid lighting systems (high-efficiency centralized light sources and controlled application of daylighting). • By 2010, fuel cells, photovoltaics, and microturbines offer cost-competitive alternatives to grid electricity. By 2020, distribution systems deliver 50% more conditioned air. • By 2020, commercial introduction of alternative refrigeration equipment with low greenhouse warming potential (e.g., Stirling cycle, Brayton cycle, acoustic, magnetic, thermal electric). • By 2020, prototype development of advanced cleaning technologies (e.g., electrolytic, ultrasonic, ozonated). • By 2030, adaptation of HVAC equipment to a new generation of power sources. <p>R&D Challenges</p> <ul style="list-style-type: none"> • The basic RD&D needed ranges from materials science to solid-state electronics, and from a better understanding of combustion fundamentals to advances in control theory. Research is also needed on behavioral and ergonomic dimensions of the user-machine relationship. • Building equipment and appliance efficiency will benefit from improvements in a wide range of thermal, mechanical, and electronic technologies (see System Concepts), as well as better systems integration, more cost-effective and reliable fabrication methods, and sustainable design concepts (e.g., use of recyclable and environmentally preferred materials, modular design, ecologically sound manufacturing). <p>RD&D Activities</p> <ul style="list-style-type: none"> • Most federal R&D on building equipment is performed by DOE. • No systematic data have been compiled on international funding levels, although activities such as the IEA Heat Pump Centre represent a potential source of such data for selected equipment types.
Recent Success
<ul style="list-style-type: none"> • Recent DOE-sponsored R&D, often with industry participation, has produced a prototype refrigerator that uses less than half the energy of the current best designs; an improved air-conditioning cycle to reduce oversizing and improve efficiency; high-performance insulating materials for demanding thermal applications; and a replacement for inefficient, high-temperature halogen up-lights (torchieres) which uses only 25% of the power, lasts longer, and eliminates a potential fire hazard.

Commercialization and Deployment

- Building equipment and appliances often vary in efficiency by 20 to 40% from the least efficient model on the market to the most efficient; this efficiency range is narrower where successful appliance standards have previously eliminated the least efficient models.
- The stock and energy intensity of equipment are growing faster than the building stock itself, as manufacturers introduce and consumers and businesses eagerly accept new types of equipment, more sophisticated and automated technologies, and increased levels of end-use services.
- The rapid turnover and growth of many types of building equipment—especially electronics for computing, control, communications, and entertainment—represent major growth in electricity demand and thus carbon emissions, but also an important opportunity to rapidly introduce new, efficient technologies and quickly propagate them throughout the stock.
- Provided that they are implemented without a significant reduction in amenities, the market success of most new equipment and appliance technologies is virtually ensured if the efficiency improvement has a 3-year payback; technologies with payback of 4 to 8+ years can also succeed in the market provided that they offer other customer-valued features (e.g., reliability, longer life, improved comfort or convenience, quiet operation, smaller size, lower pollution levels).
- Applications extend to every segment of the residential and nonresidential sectors. Major government, institutional, and corporate buyers represent a special target group for voluntary early deployment of the best new technologies.

Potential Benefits and Costs

Carbon Reductions

	2010	2020	2030
Buildings	25–50	50–100	75–150
Equipment and appliances	15–35	20–40	25–45

RD&D Expenditures

- Federal RD&D expenditures are required because the buildings industry does little R&D. DOE funding has been about \$20M/year in recent years out of a total Buildings R&D budget of about \$50M/year. A vigorous pursuit of this pathway would take an annual DOE RD&D budget of 2000–2010, \$60M/year; 2010–2020, \$90M/year; 2020–2030, \$60M/year.

Market

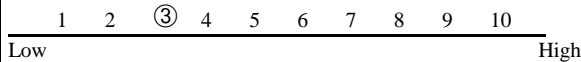
- Building equipment and appliances represent an annual market in the United States alone of well over \$200B, involving thousands of large and small companies. Certain technologies, such as office and home electronics, compete in global markets with little or no change in performance specifications.

Non-energy Benefits and Costs

- Major benefits, other than energy savings and reduced GHG emissions, include better control of indoor comfort conditions; improved health and productivity; potential for replacing CFC-based refrigeration equipment with efficient, non-ozone-depleting models; reduced air pollutant emissions.

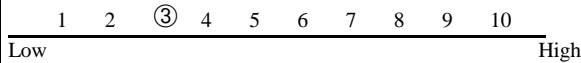
Risk Factors

Technical Risk



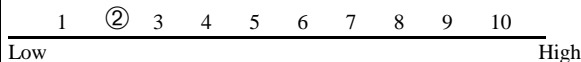
- Track record of federally funded R&D leading to commercial products.
- Small-scale units allow easier field testing, performance verification, and refinement before large-scale deployment.

Commercial Risk



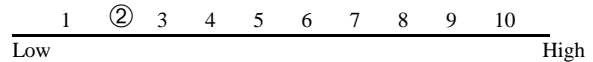
- Existing infrastructure for design, manufacturing, installation, and so on.
- Labeling, government procurement, and voluntary programs can reduce market risk to innovative suppliers.
- Minor dependence on foreign sources is easily overcome.

Ecological Risk



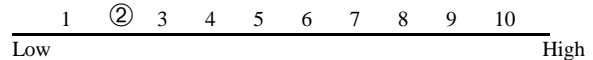
- Modest ecological risk from electronics and other equipment and materials manufacturing.
- Positive impact on air and water pollution.

Human Health Risk



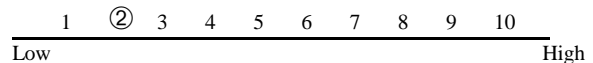
- Improved indoor air quality with better ventilation and controls can reduce health risk and improve productivity.

Economic Risk



- Cost-effective products will encounter less market resistance, provided functional and quality/reliability requirements are met.
- Public perception is favorable to introducing advanced equipment.

Regulatory Risk



- Regulations on production, marketing, and installation of building products can impede new technologies.

Key Federal Actions

- Deployment programs to leverage the RD&D investment.
- Equipment and appliance standards developed with industry.
- Federal procurement to create demand.

1.2 BUILDING ENVELOPE

Technology Description

The building envelope is the interface between the interior of a building and the outdoor environment. In most buildings, the envelope—along with the outdoor weather—is the primary determinant of the amount of energy used to heat, cool, and ventilate. A more energy-efficient envelope means lower energy usage in a building and lower GHG emissions. Advances in materials research and fenestration systems, better building practices, and increased use of renewable technologies promise to significantly lower the energy required to maintain high-quality building interior climate conditions.

System Concepts

- Control of envelope characteristics provides control over the flow of heat, air, moisture, and light into the building. These flows and the interior energy and environmental loads determine the size and energy usage of HVAC and distribution systems.
- Materials for exterior walls, roofs, foundations, windows, doors, interior partition walls, ceilings, and floors that can impact future energy use include insulation, with innovative formula foams and vacuum panels; optical control coatings for windows and roofs; and thermal storage materials, including lightweight heat storage systems.

Representative Technologies

- *Superinsulation:* Vacuum powder-filled, gas-filled, and vacuum fiber-filled panels; structurally reinforced beaded vacuum panels; and switchable evacuated panels with insulating values over four times those of the best currently available materials will soon be available for niche markets. High-thermal-resistance foam insulations with acceptable ozone depletion and global warming characteristics will allow for continued use of this highly desirable thermal insulation.
- *Advanced window systems:* Krypton-filled triple-glazed low-E windows and electrochromic glazing and hybrid electrochromic/PV films and coatings will provide improved lighting and thermal control of fenestration systems. Advanced techniques for integration, control, and distribution of daylight will significantly reduce the need for electric lighting in buildings. Self-drying wall and roof designs will allow for improved insulation levels and increase the lifetimes for these components. More durable high-reflectance coatings will allow better control of solar heat on building surfaces.
- *Advanced thermal storage materials:* Dry phase-change materials and encapsulated materials will allow significant load distribution over the full diurnal cycle and significant load reduction when used with passive solar systems.

Technology Status/Applications

- Building insulations have progressed from the 2–4 °F·h·ft²/Btu/in. fibrous materials available before 1970 to foams reaching 7 °F·h·ft²/Btu/in. Superinsulations of over 25 °F·h·ft²/Btu/in. will be available for niche markets soon. It is critical to find acceptable replacements for HCFCs in foams in order not to backslide in the use of this insulation in buildings. Improvements in window performance have been even more spectacular. In the 1970s, window thermal resistance was 1 to 2 °F·h·ft²/Btu. Now, new windows have thermal resistance of up to 6 °F·h·ft²/Btu (whole window performance). Windows are now widely available with selective coatings that reduce infrared transmittance without reducing visible transmittance. In addition, variable-transmittance windows under development will allow optimal control to minimize heating, cooling, and lighting loads.

Current Research, Development, and Demonstration

RD&D Goals

- 30/30 (R/30 insulation and 30-year life) low-slope roof options.
- Windows with 70% of adjacent wall thermal resistance and variable, controllable light transmittance.
- Mass-produced (factory-built) customized buildings with integrated envelope and equipment systems designed and sized for specific sites and climates.
- Vacuum insulations dominating several niche markets (mobile homes and freezer walls).
- On-site renewables replacing 15% of purchased energy [see photovoltaics pathway].
- 50% of building materials containing 50% recyclable materials.
- A 30% decrease in the average envelope thermal load of existing residential buildings and a 66% decrease in the average thermal load of new buildings.

RD&D Challenges

- Foam insulations that retain high thermal resistance while using blowing agents with zero ozone depletion potential and negligible global warming effect.
- Self-drying wall and roof designs to avoid moisture problems such as materials degradation.
- Electrochromic window films and electrochromic/PV hybrid window films to control energy flows and generate electricity on site.
- Techniques to distribute and control daylight to reduce electrical energy use for artificial lighting.
- Advanced durable cost-effective superinsulations to reduce heating/cooling loads.
- Advanced building simulation tools to permit better design, construction, commissioning, and operation.
- Self-calibrating multi-function micro-sensors for in situ performance and air quality monitoring.
- Thermal storage materials: typically, thermal storage in building components is achieved with heavyweight materials such as masonry. Advanced thermal storage materials need to be lightweight to integrate with elements similar to drywall, floor, and ceiling panels.

RD&D Activities

- Key agencies doing R&D on building envelopes are DOE, NIST, and several state agencies such as the Florida Solar Energy Center and the Iowa Ames Laboratory.
- DOE funding has been about \$8M/year in recent years. Funding from other agencies has been significantly less. No attempt has been made to estimate funding for private sector R&D, although it is thought to be considerably more than that of agencies and is typically directed toward specific products and problems. Total international support is also significant. Most developed countries have one to several laboratories doing research, often more fundamental than that in U.S. labs. International participants typically are 20% or more of those attending U.S. conferences on envelope research.

Recent Success

- A DOE-sponsored RD&D partnership with the Polyisocyanurate Insulation Manufacturers Association, the National Roofing Contractors Association, the Society of the Plastics Industry, and EPA helped the industry find a replacement for CFCs in polyisocyanurate foam insulation. This effort enabled the buildings industry to transition from CFC-11 to HCFC-141b by the deadline required by the Montreal protocol.

Commercialization and Deployment

- The market potential is significant for building owners taking some actions to improve building envelopes. Currently, 40% of residences are well insulated, 40% are adequately insulated, and 20% are poorly insulated. Over 40% of new window sales are of advanced types (low-E and gas-filled). In commercial buildings, over 17% of all windows are advanced types. Over 70% of commercial buildings have roof insulation; somewhat fewer have insulated walls.
- Building products are mostly commodity products. A number of companies produce them; and each has a diverse distribution system, including direct sales, contractors, retailers, and discount stores.
- A critical challenge is improving the efficiency of retrofits of existing buildings. Retrofitting is seldom cost-effective on a stand-alone basis. New materials and techniques are required.
- Many advanced envelope products are cost-competitive now, and new technologies will become so on an ongoing basis. There will be modest cost reductions over time as manufacturers compete.

Potential Benefits and Costs

Carbon Reductions

• In MtC/year for buildings overall and this pathway			
	2010	2020	2030
Buildings	25–50	50–100	75–150
Envelopes	5–10	15–30	30–60

RD&D Expenditures

- Federal RD&D expenditures are required because the buildings industry does little R&D. DOE funding has been about \$8M/year in recent years out of a total Buildings R&D budget of about \$50M/year. A vigorous pursuit of this pathway would take about an annual DOE RD&D budget of 2000–2010, \$30M/year; 2010–2020, \$45M/year; 2020–2030, \$30M/year.

Market

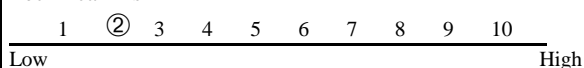
- Building structures represent an annual market in the United States of over \$70B/year and involve thousands of large and small product manufacturers and a large, diverse distribution system that plays a crucial role in product marketing. Exporting is not an important factor in the sales of most building structure products.

Nonenergy Benefits and Costs

- Major benefits, other than energy savings and reduced GHG emission, include more affordable housing; improved comfort, health, and productivity; a significant increase in recycled materials; reduced ozone depletion potential with non-CFC/HCFC foam insulations; reduced air pollutant emissions.

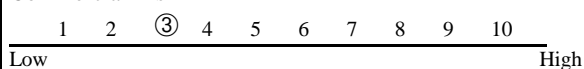
Risk Factors

Technical Risk



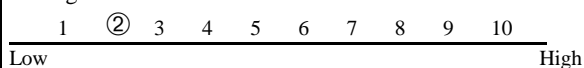
- Track record of federally funded R&D leading to commercial products.
- Materials and concepts typically are tested in other areas.

Commercial Risk



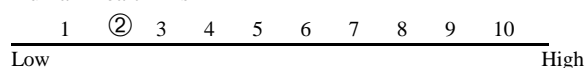
- Existing infrastructure for design, components, construction, and so on.
- Conservative industry can impede new technologies.
- Minor dependence on foreign sources easily overcome.

Ecological Risk



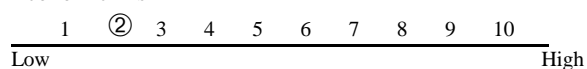
- Materials and concepts have been studied in other areas.
- Positive impact on air and water pollution.

Human Health Risk



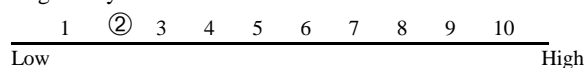
- Much installation is do-it-yourself and entails a higher risk than professional handling.
- Small risk from outgassing from materials.

Economic Risk



- Commodity market will drive out products that are not economical.
- Public perception is very favorable to implementation of advanced envelopes.

Regulatory Risk



- Regulations on production, marketing, and installation of building products can impede new technologies.

Key Federal Actions

- Deployment programs to leverage the RD&D investment.
- Building standards developed with industry.
- Federal procurement to create demand.

1.3 INTELLIGENT BUILDING SYSTEMS

Technology Description

Intelligent building systems (IBSs) would use data from design, together with sensed data, to automatically configure controls and commission (i.e., start up and check out) and operate buildings. Control systems would use advanced, robust techniques and would be based on smaller, cheaper, and more abundant sensors. These data would ensure optimal building performance by controlling building systems and continuously recommissioning them using automated tools that detect and diagnose performance anomalies and degradation. IBSs would 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 were met at the lowest possible cost.

System Concepts

- The system would consist of design tools, automated diagnostics, interoperable control systems, and sensors.
- These components would work together to collect data, configure controls, monitor operations, and correct out-of-range conditions that contribute to poor building performance.
- IBSs would ensure that essential information, especially the design intent and construction implementation data, would be preserved and shared across many applications throughout the lifetime of the building.
- Equipment and system performance records would be stored as part of a networked building performance knowledge base that would grow over time and provide feedback to designers, equipment manufacturers, and building operators and owners.

Representative Technologies

- DOE is developing computer-based building commissioning and operation tools to improve the energy efficiency of *existing* buildings. It is also investing in the next generation of building simulation programs that could be integrated into design tools.

Technology Status/Applications

- Savings from improved operation and maintenance procedures could save more than 30% of the annual energy costs of existing commercial buildings, even in many of those buildings thought to be working properly by their owners/operators. These technologies would have very short paybacks because they would ensure that technologies were performing as promised, for a fraction of the cost of the installed technology.

Current Research, Development, and Demonstration

RD&D Goals

- Design environments with fully and seamlessly integrated building design tools that support all aspects of design and provide rapid analysis; design suggestions; quick and easily understood data interpretation; automatic generation of all design documents; and a building electronic data structure that supports start-up, operation, maintenance, and renovation of the building by IBS.
- Automatic operation of buildings by automatically sensing installed equipment, checking for proper installation, generating control algorithms, implementing optimal adaptive control, diagnosing and correcting operating episodes that produce inefficient or uncomfortable conditions, managing maintenance, and providing performance data in usable forms for operators of new and existing buildings, facility managers, and owners.

RD&D Challenges

- Design tools: enhanced analytical capabilities, integration with the design environment, automated design and analysis capability, design databases, visualization, and high-level monitoring and reporting tools.
- Automated diagnostics: diagnosticians, plug and play capabilities, automated real-time purchasing, and advanced data visualization.
- System interoperability and controls: integrated control networks; adaptive, optimized, self-generating control algorithms; and advanced control techniques.
- Sensors: materials properties, microscale sensors, microelectronic sensors, multiple-sensor arrays, protocols for using new sensors, and new sensing technologies.
- Visualization: use of supercomputers, advanced computational methods, and virtual reality systems to permit real-time visualization of designs and design changes, including lighting, thermal flows, and air quality.
- Early priorities include enhancing design tool integration, developing automated diagnosticians, implementing remote data collection and visualization, and developing sensors.

RD&D Activities

- DOE is funding work along with the California Institute for Energy Efficiency, Honeywell, Johnson Controls, Landis and Staefa, EPRI, and Pacific Gas and Electric Company. International efforts include a European Union-funded effort to develop adaptive control techniques for improving the thermal environment for JOULE III—SEC.

Recent Success

- Energy 10: models passive solar systems in buildings.
- DOE 2: international standard for whole building energy performance simulation has thousands of users worldwide.
- The International Alliance for Interoperability is setting international standards for interoperability of computer tools and components for buildings.

Energy-Efficient Technologies

2. Industry

- 2.1 Energy Conversion and Utilization**
- 2.2 Resource Recovery and Utilization**
- 2.3 Industrial Process Efficiency**
- 2.4 Enabling Technologies**

2.1 ENERGY CONVERSION AND UTILIZATION

Technology Description

A significant portion of the carbon emissions from the industrial sector are associated with the conversion and utilization of energy. A systems approach to energy conversion and utilization incorporating the best technologies could have a significant impact on GHG emissions and improve the competitive posture of the industrial sector. Many opportunities exist for improving the efficiency of energy generation, including ATS, fuel cells, gasification technologies, and advanced combustion technologies. As many opportunities exist in energy utilization, including economical use of waste heat and thermal cascading by using a systems approach to mill/plant design to minimize generation of low level heat.

System Concepts

- The industrial sector could significantly reduce GHG emissions by a combination of improvements in energy utilization efficiency, switching to low-GHG fuels, gasification of waste materials into useful fuels, advanced on-site high-efficiency, and low-GHG-emissions generation technologies such as advanced combustion turbines and fuel cells.
- Modern design techniques and a whole systems approach to mill/plant design could minimize the generation of excessive low-level heat that cannot be removed easily and economically.

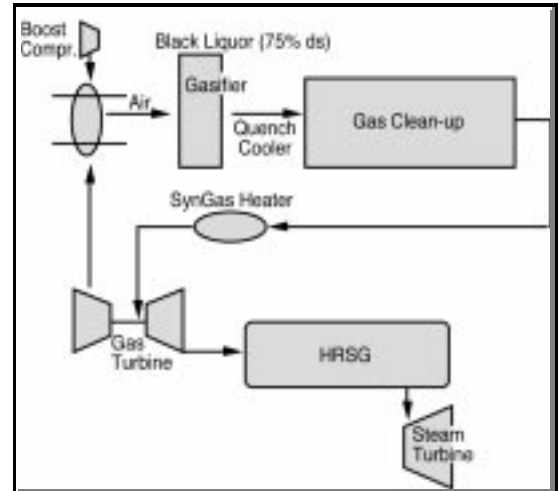
Representative Technologies

A range of technologies and process improvements under development are promising:

- ATS
- Fuel cells
- Gasification of biomass and in-plant process streams (i.e., black liquor in the pulp and paper industry)
- Waste heat utilization
- Systems approach to mill/plant design
- Co-firing of biomass
- Advanced combustion technologies

Technology Status/Applications

- Energy generation technologies currently used by industry typically have thermal efficiencies ranging from 25 to 55%; the next generation of energy generation technologies promises thermal efficiencies ranging from 45 to 80%. This average 20% improvement would significantly reduce the amount of fuel required, and hence GHG emissions, to generate the energy required. Additionally, aggressive development and deployment of distributed on-site generation technologies could avoid transmission and distribution losses, which average approximately 7%.
- Energy utilization gains of as high as 30% could result from advanced energy utilization technologies and more integrated mill/plant designs.
- Use of in-plant wastes and residues from production processes to generate energy is a promising area for reducing energy intensity and GHG emissions. RD&D is needed to increase the use of this technology and make it more cost-effective.



Current Research, Development, and Demonstration

RD&D Goals

- Significant gains in energy generation efficiency and GHG reductions could result from aggressively switching to highly efficient on-site generation technologies, such as advanced combustion turbines in combined cycle and fuel cells. Switching to low-carbon fuels such as natural gas or zero-carbon fuels such as biomass could bring additional GHG reductions.
- The chemical, petroleum refining, forest products, and steel industries account for over 2/3 of the energy use of the industrial sector. Therefore, efforts will continue to focus on these four industries.

RD&D Challenges

- Basic and applied research into advanced, low- or zero-GHG-emission generation technologies.
- In the near term, advanced industrial turbines with combined cycle generation, higher combustion efficiencies, waste heat utilization, a systems approach to mill/plant design, and biomass and black liquor gasification.
- Also in the near term, improvements in manufacturing such as advanced drying, more efficient lighting, and high-efficiency motor systems and drives for higher energy utilization efficiency.
- In the long term, continued work on advanced industrial turbines and noncombustion techniques such as fuel cells for high-efficiency energy generation.

RD&D Activities

- RD&D activities related to this pathway are sponsored by DOE, EPA, NIST-ATP, and other federal agencies. This pathway will work closely with and leverage past investments in these program areas.

Recent Success

- A major carbon-reducing technology for industry between now and 2010 is a high-efficiency, environmentally superior, natural gas-fired turbine that cogenerates electricity and steam. The ATS program is developing these turbines for industry and electrical generation. When introduced in 2001, they will have CO₂ emissions 21 to 61% lower and thermal efficiencies 15% higher than conventional turbines and will reduce electrical generation costs by 10%.

Recent Success (continued)

- Integrated gasification of biomass and black liquor combined cycle technologies will impact the pulp and paper industry in two ways: by improving energy self-generation and use of waste biomass produced at mill sites and by improving forest management practices. The waste biomass and the black liquor are gasified and fired in an advanced gas turbine for high-efficiency electrical and steam generation. Black liquor gasification was demonstrated at the pilot scale in a pulp mill in 1995, and a near-commercial-scale biomass gasifier is under construction and expected to be operational in 1997.

Commercialization and Deployment

- Industry is already making substantial investments in commercializing and deploying economical technologies: combusting wastes and residues, fuel switching in combustion systems, better understanding of large energy consuming processes, and energy cascading from high temperature to lower temperature uses within plants. Availability of capital and the competition for R&D funds will impact deployment of new technology. Cost competitiveness with existing technologies will be achieved when the newer technologies have completed their R&D cycles.

Potential Benefits and Costs

Carbon Reductions

Industrial sector

	1997 (base)	2010	2020	2030
BAU case quads	34.4	39.7	43.8	48.5
Eff. case(mod) quads		36.6	38.3	40.5
MtC reductions	0	25–50	65–95	100–140
(35% allocation to this pathway)				
MtC reductions		9–18	23–33	35–50

The estimated MtC reductions for the sector have wide ranges to account for uncertainties in market adoption and economics.

Assumptions (for all industrial sector):

- Growth rate in manufacturing output of 2.1%/year.
- For BAU case, energy intensity decreases by 1.1%/year (0.5%/year increases in efficiency and .6% composition).
- For the efficiency case, there is an additional 0.35%/year increase in energy intensity.
- Additional 10–12, 22–25, and 30–40 MtCe/year in 2010, 2020, and 2030, respectively, attributable to accelerated use of new technologies: ATS, biomass, and black liquor gasification.
- 35% of energy savings and carbon reductions in industrial sector attributable to the energy conversion and utilization pathway. This pathway has the potential for the largest impact in the industrial sector because of the use of new, more efficient energy technologies.

RD&D Expenditures

- Total federal expenditures in FY 1997 are estimated to be approximately \$50M.
- Substantial R&D resources are required to accomplish the objectives of this technology pathway. A number of promising technologies will need cost sharing from the federal program for industry to obtain the needed information from the R&D process and then commercialize the technologies.
- Annual federal RD&D budget required for this pathway: 2000–2010, \$140M/year; 2010–2020, \$210M/year; 2020–2030, \$140M/year.

Market

- The markets for the technologies developed in this pathway will be industry in general; however, the primary focus will be on the largest energy users: chemicals, steel, petroleum refining, and forest products.

Nonenergy Benefits and Costs

- More competitive industrial sector; export potential for advanced turbines, industrial fuel cells, and black liquor and biomass gasifiers; lower energy costs

Risk Factors

Technical Risk

1	2	③	4	5	6	7	8	9	10
Low									High

Commercial Risk

1	②	3	4	5	6	7	8	9	10
Low									High

Ecological Risk

1	2	③	4	5	6	7	8	9	10
Low									High

Human Health Risk

1	②	3	4	5	6	7	8	9	10
Low									High

Economic Risk

1	2	3	④	5	6	7	8	9	10
Low									High

Regulatory Risk

1	2	3	④	5	6	7	8	9	10
Low									High

- Uncertainties regarding the speed and nature of utility deregulation could hinder penetration of ATS.

Key Federal Actions

- Government/industry cost sharing partnerships are essential to the success of this pathway.
- Federal investment needs to be sustained.
- Utility restructuring to favor industrial self-generation and power sales could accelerate these technologies.

2.2 RESOURCE RECOVERY AND UTILIZATION

Technology Description

Resource recovery and utilization is waste minimization through recovery within the industrial process (treated largely under process efficiency) and/or end-of-pipe and post-consumer recovery and use of materials, process byproducts, chemical reactants, gases, solvents, diluents, steam, cooling water, and other waste. These materials can be reprocessed to reduce the burden on feedstocks, to make different products, to be used as fuels, or to be recycled. The practice mitigates CO₂ by eliminating the energy costs for replaced feedstocks and waste treatment and by improving plant efficiency. An example of recovery, recycle, and reuse is a process used at a cement kiln owned and operated by the Pasamaquoddy Tribe (see photo) wherein a waste (K₂O) is used in a scrubber and converted to K₂SO₄, which is sold as fertilizer. Distilled water is recovered from the crystallizer, and waste heat from the kiln is used to operate the crystallizer.

System Concepts

- Resource recovery and utilization involves cradle-to-grave stewardship over industrial products. In the example cited, the reuse of K₂O mitigates CO₂ emissions because it displaces fertilizer production elsewhere and avoids the cost of disposing of the waste.
- Components of the technology are advanced separations, improved chemistry, improved catalysts, advanced materials, optimal process and engineering design, sensors and controls, biotechnology, post-consumer processing, market sensitivity, and close integration between producers, users, and post-consumer processors.
- This pathway includes technologies that impact the other three industry technology pathways, particularly energy conversion and utilization and industrial process efficiency.

Representative Technologies

- Recovery—filters, advanced separations, improved chemistry, sensors and controls.
- Reuse—recycling, improved chemistry, new markets, industrial ecology.
- Improved understanding of fundamental chemistry and biotechnology advances allow use of CO₂ and other recovered byproducts as feedstocks: algae to form carbonates, bioenzymes for biodegradable polymers, biomanufacturing, biomembranes for selective separations, bioremediation of wastes, biomass and agricultural waste for use as chemicals and as fuels when co-fired with fossil fuels, chemicals from CO₂, and fuels from plastics and rubber. Capture of methane (coal beds, landfills, agricultural), capture of CO and NO_x.
- Industrial ecology integrates producers and consumers closely to minimize waste; one plant's waste is another's feedstock. Transportation costs are avoided by siting plants in close proximity. Synergetic cost-effective relationships can result in energyplexes or ecoplexes where utilities, producers, and consumers are part of an integrated community.

Technology Status/Applications

- Major industry groups avoid 39.9 MtC/year (potential is 140.5 MtC/year).
- Industry recovers about 28% of potentially recoverable waste; thus 28% recovery must be viewed as cost-effective.



Current Research, Development, and Demonstration

RD&D Goals

- Identifying nontoxic alternative reagents through improved chemistry; improving separations to capture and recycle materials, byproducts, solvents, and process water; identifying new uses and markets for recovered materials, including ash and other residuals such as scrubber sludges.
- Industries of the future, agriculture, textiles manufacturers, utilities, and municipal waste facilities.

RD&D Challenges

- Better understanding of fundamental chemistry, advances in biotechnology, advanced computing and modeling capabilities for improved process and engineering design, and technology transfer.
- Improved chemistry, improved separations, new markets, improved sensors and controls, improved process and engineering design, and durable advanced materials.

RD&D Activities

- Industries of the Future solicitations have funded projects to improve energy efficiency and reduce waste; participants include industry, DOE laboratories, and academia. DOE has cooperative agreements with the Energy and Environmental Research Center and the Western Research Institute that require 50% cost sharing by industry; many of these projects focus on waste reduction.
- Ongoing activities include use of biomass feedstocks as an alternative to use of oil for deriving industrial chemicals, feedstock preparation so industry can confidently use recovered along with virgin materials in the production processes, and techniques for effective separation of materials in plant and post-consumer streams for recovery and reuse. Recovery of plastics and conversion to chemicals used in the manufacture of new polymers is another area of ongoing R&D.

Recent Success

- Recovery of methanol from industrial process, eliminating disposal of spent methanol via combustion.
- On-site recycling of chips resulting from machining of aluminum.
- Continuous preheating of steel scrap using furnace heat during steel production.
- An electrochemical de-zincing process that removes zinc from galvanized steel and recovers it for reuse.
- Recovery of salt from process brines to enable cost-effective saltcake recycling.

Commercialization and Deployment

- Technologies that compete with resource recovery and utilization include waste disposal in landfills, incinerators, and approved hazardous waste disposal sites.
- Advantages—initially less expensive and more convenient. Disadvantages—industry and the public do not realize the benefits of recovery, recycle, and reuse. Eventually, environmental cleanup, remediation, and brownfields-type recovery projects may be required.
- Improved chemistry, sensors and controls, materials, process and engineering design, biotechnology, and technology transfer are needed to develop alternative recovery, recycle, and reuse options, including new markets.

Potential Benefits and Costs

Carbon Reductions:

(All industrial sector)

	1997 (base)	2010	2020	2030
BAU case quads	34.4	39.7	43.8	48.5
Eff. case(mod) quads		36.6	38.3	40.5
MtC reductions	0	25-50	65-95	100-140

The estimated MtC reductions for the sector have wide ranges to account for uncertainties in market adoption and economics.

(15% allocation to this pathway)

MtC reductions	4–8	10–14	15–18
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- Assumptions (for all industrial sectors):
- Growth rate in manufacturing output of 2.1%/year.
- For BAU case, energy intensity decreases by 1.1%/year (0.5%/year—increases in efficiency and 0.6%—composition).
- For efficiency case, energy intensity increases by an additional 0.35%/year.
- Additional 10–12, 22–25, and 30–40 MtC/year in 2010, 2020, and 2030, respectively, attributable to accelerated use of new technologies: ATS, biomass, and black liquor gasification.
- 15% of energy savings and carbon reductions in industrial sector are attributable to this resource recovery and utilization pathway.

RD&D Expenditures

- Total federal RD&D expenditures in FY 1997 are estimated to be approximately \$23M.
- Substantial R&D resources are required to accomplish the objectives of this technology pathway. Several promising technologies will need cost sharing from the federal program for industry to obtain the needed information from the R&D process and then commercialize the technologies.
- Annual federal RD&D budget required for this pathway: 2000–2010, \$60M/year; 2010–2020, \$100M/year; 2020–2030, \$60M/year.

Market

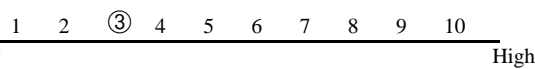
- Seven major industries—including rubber and oils, chemicals and plastics, wood and paper, textiles, food and agriculture, and construction—offer the potential to save 140 MtC/year; they mitigate 40 MtC/year using existing technologies.

Nonenergy Benefits and Costs

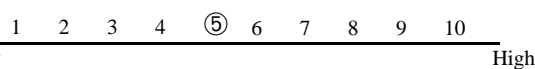
- Reductions of CH₄, CO, and NO_x as surrogates for CO₂ as well as GHG results in equivalents of 8, 40, and 21 tons, respectively, per ton of CO₂, as well as benefits to the environment, particularly ground-level ozone reduction. Reduced impacts on remaining landfill capacity and reduced need for incinerators and approved hazardous waste sites.

Risk Factors

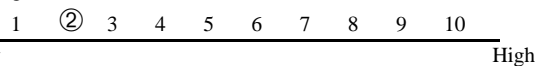
Technical Risk



Commercial Risk

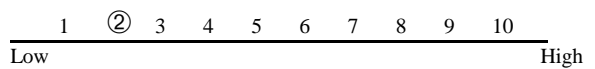


Ecological Risk



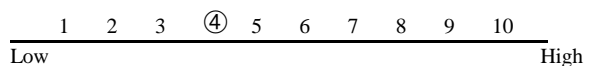
- Sustainable positive impact is expected as a result of more efficient use of materials and resources.

Human Health Risk

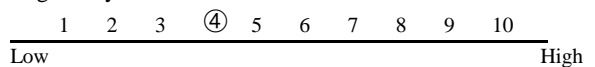


- Positive impact because of more efficient use of resources.

Economic Risk



Regulatory Risk



Key Federal Actions

- Federal support for research in fundamental and applied chemistry, advanced separations, biotechnology.

2.3 INDUSTRIAL PROCESS EFFICIENCY

Technology Description

A significant source of carbon emissions from the industrial sector may be process material and energy inefficiencies in primary or secondary manufacturing. These contribute to GHG emissions through both excess energy expenditures (increasing fossil fuel consumption) and generation of waste byproducts. Waste generation represents inadequate use of carbon-containing feedstocks and requires energy expenditure for treatment/abatement. Increases in unit process efficiency through individual process optimization or new process introduction will reduce GHG emissions and offer the potential for increased growth at reduced environmental risk.

System Concepts

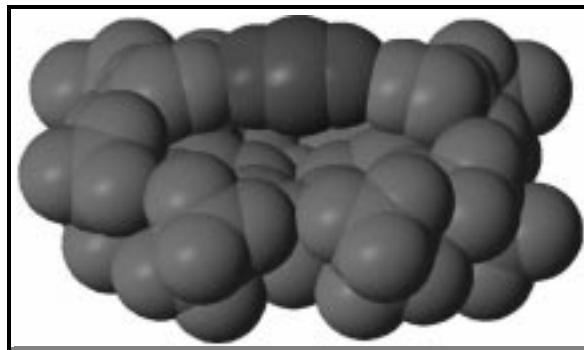
- Process efficiency is enhanced through single-process optimization or process substitution in the principal manufacturing steps of raw material primary conversion, secondary or value-added processing, and product separation. It also results from overall optimization of a manufacturing chain with resulting improvements in material and energy balance.

Representative Technologies

- Many opportunities exist for improving process energy and materials efficiency in unit operations via new or more selective catalysts, advanced separations, new material- and energy-efficient reactor concepts, and the further development and introduction of biotechnology/bio-derived materials.

Technology Status/Applications

- Technologies such as catalysts, membranes for separations, and bio-derived materials are already in the marketplace in the production of both commodity and specialty products, particularly in the materials and chemical processing industries. Such technologies already allow the manufacture of many common products today (see Commercialization section). The biggest gains to be made in GHG reduction in industrial process energy or carbon-feedstock efficiency, however, will still come from introducing these technologies into new processes (e.g., membranes as substitutes for energy-intensive distillation separations or new process introduction using bio-based feedstocks) or enhancements in current practices (e.g., enhancing selectivity in partial catalytic hydrocarbon oxidation or developing more energy-efficient process reactors). These technologies will benefit both commodity production (in the form of incremental process improvement yielding gains in energy efficiency) and the generation of specialty products (where more significant savings in waste generation are likely to result).



CO₂ conversion catalysts.

Current Research, Development, and Demonstration

RD&D Goals

- Catalysis—target processes for improvement are selective oxidation, hydrocarbon activation, byproduct and waste minimization, stereoselective synthesis, functional olefin polymerization, alkylation, living polymerization, and alternative renewable feedstocks.
- Advanced separations—membrane separations (advanced inorganic membranes, ruggedized membranes, selective membranes, antifouling), reactive separations, separative reactors.
- Development of biotechnology/bio-derived materials—biofeedstocks that directly displace fossil-derived products (modified or alternative processes), improving the performance of biocatalysts.
- Advanced chemical reactors—short contact-time reactors, reactors for nonthermal processes (plasma, microwave, photochemical), reactors for alternative media or dry processing, flexible processing units.

RD&D Challenges

- Specific R&D needs that impact these technology areas include improved understanding and prediction of chemical and material behavior, materials fabrication methods, in situ and/or rapid analytical protocols and process screening procedures, and computational tools.

RD&D Activities

- RD&D activities relating to these technology areas are sponsored by DOE, DOC, DOD, NSF, and EPA. Comparable investments in these technology areas are made abroad.

Recent Success

- Many recent examples of industrial successes and implementation of new technology exist. For example, in the membrane area, Pittsburgh Plate Glass has successfully installed an ultrafiltration and reverse osmosis system to remove paints and reuse the water in the process. Caterpillar has developed and installed, in a cost-shared project with DOE, a system for recovery and reuse of paints in its production process. Improvement in catalysts and their uses is another area where industry has implemented improved processes and is working on other processes involving converting polymers and deriving chemicals from biomass feedstocks.

Commercialization and Deployment

- Applications of many of the described technologies already have an impact in the marketplace. For example, catalytic processes are responsible for about 75% of chemical and petroleum processing products by value. Catalytic processes generate about \$900B in products annually. The ready acceptance of certain applications of these technologies reduces barriers to implementation of process improvements or their application in new processes. Powerful drivers still exist for implementing advancements in these technologies for GHG reduction. The estimated total annual consumption of energy (fuels and electricity) by the U.S. chemical process industries is 5.8 quads; nearly 43% of that (2.5 quads) is required for separation processes, including distillation, extraction, adsorption, crystallization, and membrane-based technologies. Any process facilitating such separations will result in enormous savings of both energy and waste. The chief barriers to deploying of technologies are likely to be capital expenditures required for any substantial process modification, given the scale of many relevant industrial processes.

Potential Benefits and Costs

Carbon Reductions

(All industrial sector)

	1997 (base)	2010	2020	2030
BAU case quads	34.4	39.7	43.8	48.5
Eff. case(mod) quads		36.6	38.3	40.5
MtC reductions	0	25–50	65–95	100–140

The estimated MtC reductions for the sector have wide ranges to account for uncertainties in market adoption and economics.

(30% allocation to this pathway)

	2010	2020	2030
MtC reductions	8–15	20–29	30–42

Assumptions (for all industrial sectors):

- Growth rate in manufacturing output of 2.1%/year.
- For BAU case energy intensity decreases by 1.1%/year (0.5%/year–increases in efficiency and 0.6%–composition).
- For the efficiency case, there is an additional 0.35%/year increase in energy intensity.
- Additional 10 to 12, 22 to 25, and 30 to 40 MtC/year in 2010, 2020, and 2030, respectively, attributable to accelerated use of new technologies: ATS, biomass, and black liquor gasification.
- 30% of energy savings and carbon reductions in industrial sector are attributable to this industrial process efficiency pathway.

RD&D Expenditures

- Total federal RD&D expenditures in FY 1997 are estimated to be approximately \$46M.
- Substantial R&D resources are required to accomplish the objectives of this technology pathway. Several promising technologies will need cost sharing from the federal program for industry to obtain the needed information from R&D process and then commercialize the technologies.
- Annual federal RD&D budget required for this pathway: 2000–2010, \$120M/year; 2010–2020, \$160M/year; 2020–2030, \$120M/year.

Market

- Application of the industrial processes described is central to the energy- and material-intensive industries with the largest energy consumption factors (chemicals, petroleum, forest products), shipping products valued at over \$700B.

Nonenergy Benefits and Costs

- Implementing these technologies will likely result in substantial economic benefits (reduced pollution abatement costs) and result in enhanced export potential (based on the global nature of the market).

Risk Factors

Technical Risk



Low High

- Initial gains likely to be incremental.

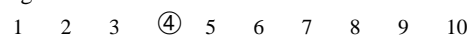
Commercial Risk



Low High

- May mandate capital investment.

Ecological Risk



Low High

- Sustained positive impact due to efficient use of materials and resources.

Human Health Risk



Low High

- Does not add substantially to current practices.

Economic Risk



Low High

Regulatory Risk



Low High

Key Federal Actions

- Government/industry partnerships are recommended to move precompetitive research forward.
- Incentives for capital investment would speed implementation.

2.4 ENABLING TECHNOLOGIES

Technology Description

Enabling technologies are new systems requiring R&D that impact all other pathways and that can provide significant improvements and new operational capabilities in many types of industries. GHGs can be reduced by increasing the efficiency of industrial processes, reducing waste and rework of products, and achieving a longer and more controlled operating life time for industrial components. Increased understanding of processes and systems required to make products will permit improvements and new manufacturing processes. The technologies range from advanced chemical reactions, materials, and measurement and controls systems, to systems and product-oriented design and processing that incorporate environmental and energy benefits in their initial and overall implementation. These types of activities will impact the reduction and more efficient use of fossil and electrical energy in current and new industrial processes.

System Concepts

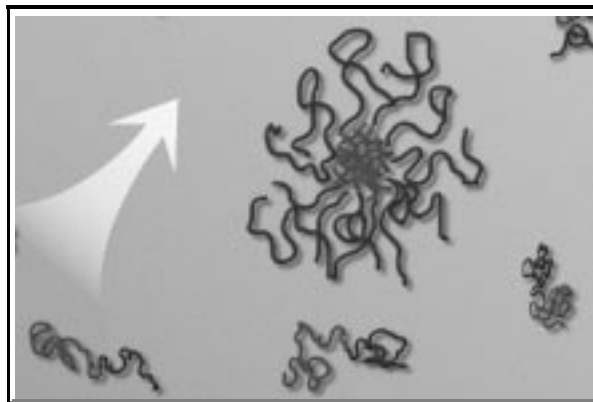
- Technologies developed through enabling technologies programs will complement and be developed cooperatively with those of other pathways, in particular energy conversion and utilization and the industrial process efficiency. Technologies included in this pathway will have positive impact in many industrial areas.
- Increased understanding of processes and application of new methods in fabricating products will impact the entire industrial sector.

Representative Technologies

- A number of enabling technologies can have positive impacts on GHG emissions, including
 - Advanced materials
 - Measurements and controls
 - New chemical reactions
 - Modeling and simulations
- Holistic product/process design (including environment and energy).
- Just-in-place processing.

Technology Status/Applications

- Increased understanding of processes and energy generation technologies can lead to both incremental and revolutionary improvements.
- Increased efficiencies and impact on reducing GHG emissions will be obtained by increasing the efficiency of processes:
 - Raising operational temperatures.
 - Developing higher temperature corrosion resistant advanced materials.
 - Finding new ways to determine and then monitor the most important process parameters affecting processes and the intelligent control of those processes.
 - Developing more efficient heat recovery and utilization.
 - Developing completely new processes.
 - Making products or energy where needed, including new and holistic design technologies incorporating environmental and energy needs from initial concepts.



Neutron scattering aids the design of environmentally friendly ways to make polymers.

Current Research, Development, and Demonstration

RD&D Goals

- New enabling technologies have a range of cost goals depending on the technologies and on the applications where they are to be used.
- Cost targets when considered on a system basis are expected to be between 0.5 to 2 times those of typical technologies.
- Applications for enabling technologies are many and encompass the various industrial segments of the economy. Every industry segment will benefit from the activities, and the efforts will be coordinated with other pathways.

RD&D Challenges

Research areas include

- New materials compositions.
- Measurement technologies and intelligent control and predictive maintenance systems.
- Increased understanding of chemicals metallurgical and biotechnology processes.
- Validated mathematical models to enable improved and integrated design and operations.
- Methods and design concepts that will enable fabricating or producing energy where it is required.
- Industrial systems components including high-temperature and corrosion-resistant production systems used for melting, heat treating, or combustion systems; chemicals and pulp and paper processing systems; processing including boilers and gasifiers; and industrial cogeneration systems.

RD&D Activities

- Ongoing R&D activities on enabling technologies include the Advanced Industrial Materials, Continuous Fiber Ceramic Composite, and ATS programs in DOE. Additional activities are in the DOC ATP program and in EPA.

Recent Success

- A high-efficiency, recuperated industrial gas turbine for the generation of electricity recently was announced. The increased firing temperature was made possible through developments in the casting of advanced single crystal superalloy airfoils.
- Currently an advanced intermetallic alloy, Ni₃Al, is being used for rolls in the heat treating of steels and as metalforming dies.

Commercialization and Deployment

- The industrial segment of the economy is substantial and enabling technologies are impacting every industrial sector. New materials are being introduced in the manufacturing of steel, new measurement systems and in situ temperature measurements in harsh environments have been developed and are being used in industry; understanding of chemicals processes is leading to improved processes; and new capabilities in design and modeling methodologies are reducing the energy usage and GHG emissions of production plants.
- The introduction of new technologies is often sensitive to initial cost, and cost benefits must be made on life cycle benefits.
- Success rests on sustained development efforts coupled with implementation efforts. Thus partnering of government, industry, universities, and national laboratories is critical. Industry is eager to deploy cost-effective technologies and improved enabling technologies for process improvements to stay competitive in the world market.

Potential Benefits and Costs

Carbon Reductions

(All industrial sector)

	1997 (base)	2010	2020	2030
BAU case quads	34.4	39.7	43.8	48.5
Eff. case(mod) quads		36.6	38.3	40.5
MtC reductions	0	25–50	65–95	100–140

The estimated MtC reductions for the sector have wide ranges to account for uncertainties in market adoption and economics.

(20% allocation to this pathway)

MtC reductions	5–10	13–19	20–28
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Assumptions (for all industrial sectors):

- Growth rate in manufacturing output of 2.1%/year.
- For BAU case, energy intensity decreases by 1.1%/year (0.5%/year—increases in efficiency and .6%—composition).
- For efficiency case, there is an additional 0.35%/year increase in energy intensity.
- Additional 10–12, 22–25, and 30–40 MtC/year in 2010, 2020, and 2030, respectively, attributable to accelerated use of new technologies: advanced turbine systems, biomass and black liquor gasification.
- 20% of energy savings and carbon reductions in industrial sector attributable to this enabling technologies pathway.

RD&D Expenditures

- Total federal RD&D expenditures in FY 1997 are estimated to be approximately \$31M.
- Substantial R&D resources are required to accomplish the objectives of this technology pathway. A number of promising technologies will need cost sharing from the federal program for industry to obtain the needed information from R&D process and then commercialize the technologies.
- Annual federal RD&D budget required for this pathway: 2000–2010, \$80M/year; 2010–2020, \$130M/year; 2020–2030, \$80M/year.

Market

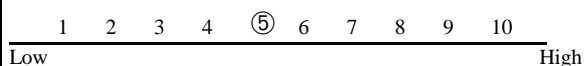
- The energy impacts will be across the various energy sectors. Reductions will occur related to natural gas, electric power, coal, and oil.

Nonenergy Benefits and Costs

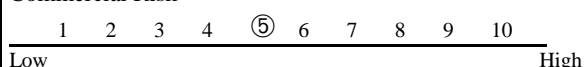
- New technologies will be highly valued and also suitable for export. The industrial sector will remain strong due to the use of new and advanced systems and the creation of new intellectual property. The advances will strengthen current industries and generate new industries and areas of commerce.

Risk Factors

Technical Risk

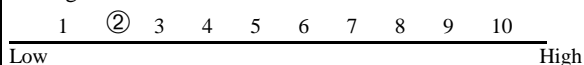


Commercial Risk



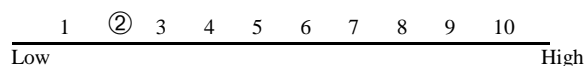
- Requires successful developments and commercialization.

Ecological Risk



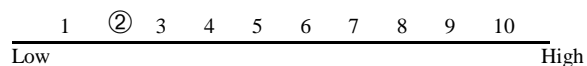
- Technologies inherently ecological.

Human Health Risk

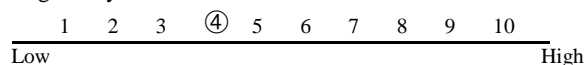


- Technologies inherently ecological.

Economic Risk



Regulatory Risk



Key Federal Actions

- Federal actions include facilitation and coordination; enhancement of partnerships between government, industry, universities, and national laboratories; and sustained investment in R&D.

Energy-Efficient 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

3.1 ADVANCED CONVENTIONAL VEHICLE

Technology Description
<p>The advanced conventional vehicle applies near-term design and technology advances to a light-duty vehicle with a conventional drive train. Fuel economy gains are obtained from a combination of reductions in the vehicle's resistive forces (aerodynamic drag, rolling resistance, and inertial and weight drag) and increases in drive train efficiency (the efficiency with which the vehicle transforms fuel energy into power at the wheels). Benefits include non-drive train improvements to vehicles with unconventional drive trains. The technologies that this pathway addresses will have applications in the other four transportation pathways.</p> <p>System Concepts</p> <ul style="list-style-type: none"> • Weight reduction: lightweight materials; redesign for equal structural integrity with less material. • Drive train system efficiency improvement: reduced friction and pumping losses, higher thermodynamic efficiency, and so on. • Reduced aerodynamic drag and rolling resistance: smoother body shape and design, better tires. <p>Representative Technologies</p> <ul style="list-style-type: none"> • Supercomputer structural design, direct injection diesel and stratified-charge gasoline engines, variable valve control (VVC), continuously variable transmissions (CVTs), aluminum and graphite composite materials, underbody panels. <p>Technology Status/Applications</p> <ul style="list-style-type: none"> • Current mid-size car \approx 27–28 mpg (EPA). • Best mid-size car = 49 mpg (EPA) VW Passat turbocharged diesel with manual transmission, without advanced materials, special tires, advanced aero. • Cost-effectiveness is a major issue for many of the technologies, especially with low gasoline prices.
Current Research, Development, and Demonstration
<p>RD&D Goals</p> <ul style="list-style-type: none"> • By 2001, develop and validate a vehicle systems concept that will achieve 45 mpg for a mid-size car without life-cycle cost or performance/reliability/safety/emissions (PRSE) penalty [DISC (direct-injection, stratified-charge) engine, 20% weight reduction, .006 rolling resistance coefficient (RRC) tires, .27 C_D, 5-speed automatic transmission]; equivalent light truck goal: 33 mpg. • By 2005, develop and validate a vehicle systems concept that will achieve 52 mpg for a mid-size car without cost/PRSE penalty (DISC engine, 30% weight reduction, .005 RRC tires, .24 C_D, CVT) or 60 mpg [w/turbocharged direct injection (TDI) diesel with advanced particulate, NO_x controls]; equivalent light truck goal: 39/45 mpg. <p>RD&D Challenges</p> <ul style="list-style-type: none"> • Cost is an issue for all of the technologies with possible exceptions of C_D reduction, advanced tires. • Cost, recycling, rapid production, repair are critical issues for carbon fiber structures; cost and repair are critical issues for aluminum. • Control effectiveness, longevity are key challenges to lean NO_x catalysts, especially for diesels; also, GHG concerns highlight need to reduce N_2O emissions. • Reducing particulate emissions from diesels, especially with proposed new EPA standards for fine particulates. • Combustion control, longevity of high-pressure fuel injectors, cost are key challenges to DISC engine. • Successful completion of these challenges will allow the application of these technologies to the full range of surface transportation vehicles, including advanced light-duty vehicles. <p>RD&D Activities</p> <ul style="list-style-type: none"> • All enabling technologies are being pursued worldwide by original equipment manufacturers and suppliers. • American Iron and Steel Institute is pursuing lightweight steel; Alcoa and others are pursuing aluminum bodies. • DOE recently has expanded research on advanced diesels to light-duty applications. • DOE is spending about \$13 million (FY 1997) on lightweight materials for light-duty vehicles: in order of funding, aluminum, polymer composites, cast steel and iron, and magnesium/titanium (material cost).
Recent Success
<ul style="list-style-type: none"> • Ford has developed a CVT compatible with larger, high-torque engines such as its Duratec V-6.

Commercialization and Deployment

- Most applicable technologies introduced in *some* commercial application in the United States or overseas: aluminum body/Audi A8; TDI diesel/VW Passat TDI; CVT/Civic HX; DISC engine/Toyota D4 (Japan); VVC/Honda VTEC.
- U.S. market penetration is modest for VVT, TDI diesel (rapid penetration in Europe), low-RRC tires, all-aluminum bodies, CVT; virtually universal for first-generation structural redesign with supercomputers and high-strength/lightweight steel.
- Critical challenges to deployment: lack of strong consumer interest in greater fuel economy (VVT is a case in point—despite Honda’s technical success with it, most competing manufacturers have not adopted it because of high cost).

Potential Benefits and Costs

Carbon Reductions

- Potential carbon reductions include effects of non-drive train improvements on vehicles with unconventional drive trains (e.g., hybrids and electric vehicles).

2010	2020	2030
15–25 MtC	40–60 MtC	80–100 MtC

RD&D Expenditures

- FY 1998 DOE RD&D budget for this pathway is \$31M.
- Annual DOE RD&D budget required for this pathway: 2000–2030, \$75M/year.
- Advanced lightweight materials research will be needed well into the next century to develop enabling technologies to reduce the total material system life-cycle cost.

Market

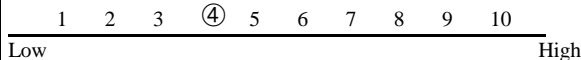
- From 300 MtC/year (2010) to 400 MtC/year (2030).

Nonenergy Benefits and Costs

- Reduce pollutant emissions, improve human health, and reduce the nation’s dependence on imported oil.

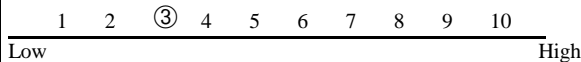
Risk Factors

Technical Risk



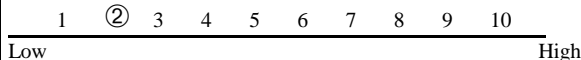
- For lightweight materials, crashworthiness and viable manufacturing techniques have not been demonstrated.
- Lean NO_x catalysts critical to the DISC engine and DI diesels require considerable further development.
- Control of fine particulates in DI diesels needs further improvement.

Commercial Risk



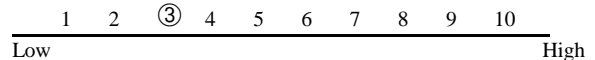
- Large shift to diesel would require major refinery infrastructure investment and would impact fuel prices.

Ecological Risk



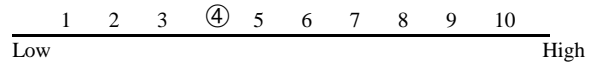
- Recycling of polymer composites is not ensured.

Human Health Risk



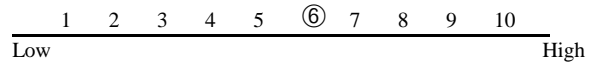
- There are ongoing concerns about diesel particulate and NO_x emissions.
- Crashworthiness of new materials is uncertain.
- Workplace risks may exist in production, recycling of new materials.

Economic Risk



- Marketability is a ubiquitous risk because increased fuel efficiency is not a widely-sought-after vehicle attribute.
- New structural materials may expose vehicle manufacturers to greater liability risks because of lack of industry experience in design and manufacture and lack of real-world safety experience.

Regulatory Risk



- Tighter NO_x standards could impact feasibility of DISC, TDI diesel technology; tighter particulate standards could affect diesels.

Key Federal Actions

- Some market transformation measures may be necessary if cost goals are not met—higher fuel taxes, new fuel economy standards, “feebates.”
- Without strong market transformation, increased federal sponsorship of RD&D would be necessary for technology development because of lack of market stimulus, high market risk.

3.2 FREIGHT VEHICLES

Technology Description

Freight vehicles (class 7 and 8 trucks and rail) are essential to the economic vitality of the nation. Diesel engines are the dominant motive source for these vehicles. Vehicle efficiency can be increased by as much as 50% with a new generation of ultra-high-efficiency diesel engines that use advanced emissions control technology, coupled with improved aerodynamics and reduced rolling and parasite power losses. Successful development and commercialization of engines with 50% efficiency will significantly reduce transportation oil use, emissions (including CO₂), and related costs to the economy.

System Concepts

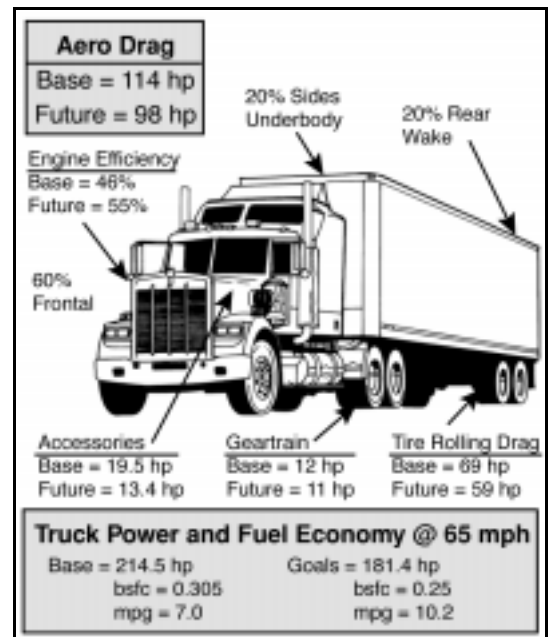
- Four-stroke, direct-injection diesel engines (with high peak cylinder pressures, thermal barrier coatings, high-pressure fuel injection systems, and turbocharging) are being developed.
- Lightweight materials, truck aerodynamics and advanced tires are being developed to improve overall fuel economy.
- Hybrid electric vehicles or regenerative braking may have application in local delivery vehicles.
- Laser glazing of rails, flywheels, diesels with oxygen-enriched air systems and fuel cells are being considered for locomotives.

Representative Technologies

- High-pressure, common-rail fuel injection, bottoming cycles, friction and wear reduction.
- Oxygen-enriched combustion air technology for locomotive diesel engines.
- Software technology to improve vehicle aerodynamics.

Technology Status/Applications

- Virtually all heavy-duty trucks and the entire fleet of locomotives are diesel powered, and there is an increasing trend to dieselize the medium-duty trucks as well. New advanced technologies for emission controls are required.
- Fuel cells are considered a long-term option. An active locomotive fuel cells program is being pursued by industry.
- Software tools are being developed to provide design guidance to reduce aerodynamic drag.



Current Research, Development, and Demonstration

RD&D Goals

- By 2004, develop enabling technologies that will
 - Lead to a fuel efficiency of 10 mpg (at 65 mph) for class 7 and 8 trucks.
 - Reduce class 7 and 8 truck emissions to 2 g/hp-h of NO_x and 0.05 g/hp-h particulates.

RD&D Challenges

- The challenge is to improve efficiency (thus reducing CO₂) and meet emission regulations.
 - Engine: high-pressure structural materials, in-cylinder processes and control, fuel effects.
 - After-treatment: NO_x and particulate matter.
 - Components: turbochargers, friction.
 - Simulation of flows around vehicles.
 - Emission control for a wide variety of gaseous and liquid fuels.

RD&D Activities

- DOE/OTT has a large heavy- and medium-duty diesel engine program for trucks.
- DOD/ARPA, California Energy Commission and the California Air Resources Board co-sponsor R&D projects with DOE.
- Federal Railroad Administration sponsors locomotive efficiency improvement projects.
- Analytical and modeling work are sponsored by DOE.

Recent Success

- New conceptual model of in-cylinder soot formation developed.
- Advanced multicylinder engine (expected efficiency of 52–53%) assembled at Caterpillar and being tested.

Commercialization and Deployment

- The diesel engine is the workhorse of all the heavy-duty transport modes that are responsible for most of the nation's intercity freight movement—the lifeblood of the economy. Because of low fuel consumption, high reliability, and long service life, it is widely acknowledged that the diesel engine will continue to dominate heavy-duty transport propulsion well into the next century.
- Strong coupling between efficiency and emissions controls is a significant barrier. Many engine design options currently available to manufacturers for emissions reduction involve a fuel economy penalty of 10 to 20%. In the absence of significant technology advancements, future emission regulations could affect the historical trend toward higher diesel engine efficiency.
- Stiff domestic and international competition from European and Japanese diesel engine manufacturers has reduced domestic market share. U.S. manufacturers have limited resources to identify, research, develop, and commercialize many of the promising advanced emission technologies.
- All new technologies have to meet high durability requirements.
- Fuel cells are at least 10 years from commercialization in any freight vehicle.

Potential Benefits and Costs

Carbon Reductions

	In MtC/year		
	2010	2020	2030
	7–10	15–30	25–35

RD&D Expenditures

- FY 1998 DOE RD&D budget for this pathway is \$40M.
- Annual DOE RD&D budget required for this pathway: 2000–2030, \$50M/year.

Market

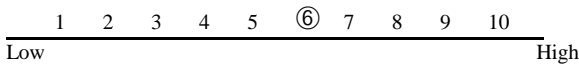
- Approximately 100 MtC/year of carbon reduction.

Nonenergy Benefits and Costs

- These technologies would reduce the nation's dependence on imported oil. Success would improve the global position of domestic heavy-duty engine manufacturers and increase the competitiveness of domestic engine manufacturers in the automotive diesel engine market largely lost to foreign producers.

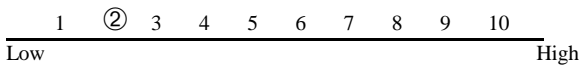
Risk Factors

Technical Risk



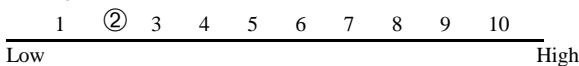
- Cost-effective after-treatment, regenerative braking, fuel cell technology are not practical commercial devices.

Commercial Risk

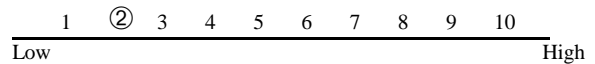


- Diesel engines are ubiquitous in the freight industry.

Ecological Risk

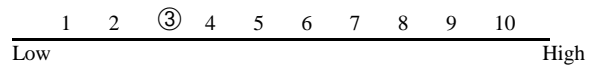


Human Health Risk



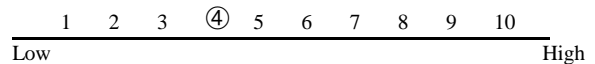
- Fine particulate matter being evaluated as health risk. Other emissions are being controlled.

Economic Risk



- Diesel engines are already an integral part of the nation's infrastructure.

Regulatory Risk



- New focus on ultrafine particulates could lead to tightened particulate standards and control challenges to diesels.

Key Federal Actions

- Federal role is to ensure U.S. diesel engine manufacturers are competitive in the marketplace in the face of heavily subsidized foreign competition.
- Federal funds are needed for the continuing improvements in freight vehicle's fuel economy to mitigate the carbon dioxide emissions from the projected increase in freight vehicle traffic over the next ten to fifteen years. In addition, federal resources are required to ensure advanced aerodynamic software tools are available to manufacturers.

3.3 HYBRID, ELECTRIC, AND FUEL CELL VEHICLES

Technology Description

The current PNGV goal is to develop advanced vehicles that are up to three times more efficient than conventional vehicles and meet low emissions standards. Hybrid electric vehicles (HEVs) use a combination of electric propulsion and an auxiliary power unit. They can be designed in either series or parallel configuration. Electric vehicles (EVs) are powered by electric drive systems that receive energy from on-board energy storage devices. EVs emit zero regulated emissions from the tailpipe. With current and projected future average generation mix for 2015, EVs yield little or no carbon reduction. Fuel cell vehicles convert fuels to electricity directly. A vehicle powered by a hydrogen fuel cell may be twice as efficient and produce extremely low to zero tailpipe emissions. Fuel cells may initially run on gasoline or alcohol fuels reformed to produce hydrogen. The fuels used and how they are produced will determine whether carbon emissions are reduced by 50 to 100% over conventional vehicles.

System Concepts

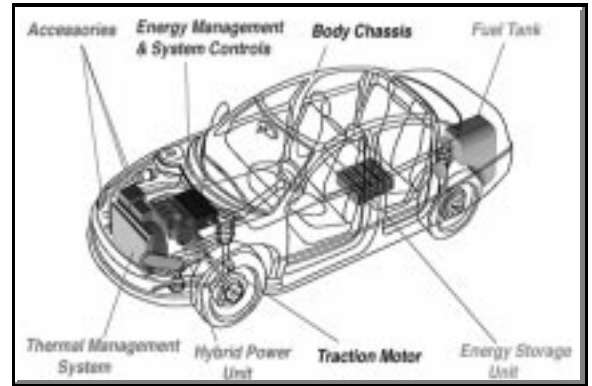
- A series HEV drives the wheels using an electric motor while drawing energy from a battery pack, which is charged by a small on-board engine or another type of power unit. A parallel HEV uses both an electric motor and a power unit to drive the wheels.
- An EV uses a rechargeable battery pack, a motor controller, an electric drive motor, and a gear reducer to drive the vehicle.
- For fuel cells, hydrogen can be stored on the vehicle or can be made on-board using gasoline or alternative fuels.

Representative Technologies

- These technologies can use combinations of high-power energy storage devices (ultracapacitors, flywheels, batteries); small, high-efficiency integrated power units (gas turbines, direct-injection diesel engines, spark-ignited engines, Stirling engines, and fuel cells); and compact electric power systems (electric drive motors, electronic controllers).

Technology Status/Applications

- As part of a multiyear 50/50 cost-shared program with DOE, GM, Ford, and Chrysler have developed prototype HEVs that are being tested and analyzed. Simulation modeling techniques are being used to optimize components.
- In 1997, several versions of EVs became available for sale/lease in selected areas. However, these cars use batteries with limited range, which prevents widespread consumer acceptance, and there are still issues with the power mix.
- Fuel cells: Proton exchange membrane fuel cells are being demonstrated on vehicles and buses.



Current Research, Development, and Demonstration

RD&D Goals

- HEVs: DOE is striving to develop HEVs with triple the fuel efficiency of conventional vehicles and comparable performance, range, safety, and cost. By 2004, the goal is to have an 80 mpg vehicle that meets Tier II emissions standards.
- EVs: Industry and government are striving to develop advanced batteries with increased range and life-cycles. The long-term EV battery targets are power density of 460W/L, specific power of 300 W/kg, energy density of 230 Wh/L, specific energy of 150 Wh/kg, and a life of 10 years.
- Fuel cells: Stack systems with a power density of 500 W/kg, specific power of 500 W/L, efficiency of 68% at 25% peak power, durability of 5000 hours, a cold start-up time to maximum power of less than 30 seconds, and a cost of less than \$50 kW must be developed.

RD&D Challenges

- HEVs: System integration and packaging, cost and durability of components, high-power battery packs, and compact high-efficiency engines.
- EVs: Cost, life, performance, weight, and range of EV battery packs. Reducing battery recharge time and optimizing battery thermal management are also important challenges.
- Fuel cells: Tolerance to CO poisoning and reductions in weight, volume, and cost. Lack of an adequate infrastructure system for new fuels (e.g., hydrogen, methanol) also is a problem.

RD&D Activities

- HEVs: DOE has related programs that conduct research on advanced gas turbines, engine materials, lightweight materials, advanced energy storage, and fuel cells. These programs are directly linked to DOE's PNGV/Hybrid Propulsion Systems Program.
- EVs: DOE has a High Power Energy Storage Program and Exploratory Technology Research Program. Other federal agencies (NASA, DOD) and private agencies have battery R&D programs of their own.
- Fuel Cells: DOE is working with industry and other federal agencies to develop fuel cells and fuel processing systems.

Recent Success

- GM, Ford, and Chrysler have numerous hybrid and electric vehicles in various stages of development. Technical feasibility of these concepts has matured, although cost and reliability barriers need continued attention.
- The nickel-metal hydride battery is approaching (in some cases attaining or exceeding) all performance goals, although cost remains an issue.
- Demonstration prototypes of fuel cell vehicles have been built and zero-emission fuel cell buses are in operation.

Commercialization and Deployment

Commercialization

- HEVs: The Big 3 automakers are working with DOE to develop production-feasible HEV propulsion systems by 1998. Vehicle commercialization will begin when the market is ready and a business case can be made. Toyota will soon market a 65-mpg hybrid called Prius.
- EVs: Almost all major manufacturers began selling/leasing some version of an EV to public and/or private fleets in 1997. GM and Honda were the first two companies to lease EVs to private individuals. Consumer leasing figures have been less than anticipated. Additional improvements need to be made to increase the range and reduce cost so that more people will find these vehicles acceptable.
- Fuel cells: Almost all major auto manufacturers are pursuing fuel cell development. Manufacturability and cost are the most significant barriers to commercialization. Size and weight must also be substantially reduced to make them competitive with alternatives.

Deployment

- HEVs: An HEV's biggest competitor is an advanced conventional vehicle. Consumer acceptance and willingness to pay a little more for a more fuel efficient, high-technology vehicle is key. Depending on the fuel used in the HEVs, there will be minimal refueling infrastructure challenges that may affect widespread deployment.
- EVs: An EV's competition is an advanced conventional vehicle and an HEV. HEVs will have low GHG emissions and possibly low criteria emissions along with a range comparable to a conventional vehicle. Society will have to weigh the benefits of having a vehicle with limited range and no tailpipe emissions against the benefits of having an advanced vehicle with possibly lower emissions.
- Fuel cells: Fuel cell vehicles can combine the zero emissions of an EV and the range of conventional vehicles. Fuel cell vehicles have the potential to require less maintenance and have a more durable engine than conventional vehicles. Larger investments and longer lead times for the fuel cells to mature make this technology lag EVs and HEVs.

Potential Benefits and Costs

Carbon Reductions

- The combination of advanced vehicles will result in GHG emissions reductions of 10–15 MtC by 2010, 25–45 MtC by 2020, and 50–75 MtC by 2030.

RD&D Expenditures

- The federal government and its industry partners will need to continue to invest in EV, HEV, and fuel cell technologies to make the pathways successful. FY 1998 DOE RD&D budget for this pathway is \$104M. Annual DOE RD&D budget required for this pathway: 2000–2010, \$230M/year; 2010–2030, \$250M/year. While the budgets for outyears are speculative, technology-driven opportunities for carbon reductions in this sector will continue to be large well into the next century.

Market

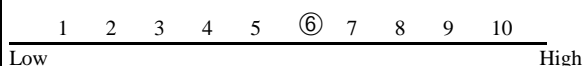
- From 300 MtC/year (2010) to 400 MtC/year (2030).

Nonenergy Benefits and Costs

- Besides reducing emissions, HEV, EV, and fuel cell technologies will improve human health and reduce dependence on imported petroleum.

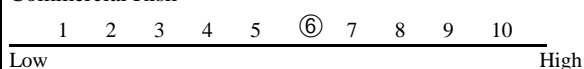
Risk Factors

Technical Risk



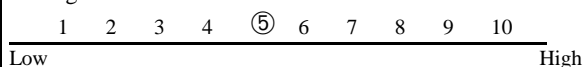
- Battery improvement, system integration processes, infrastructure availability, and component optimization, are issues.

Commercial Risk



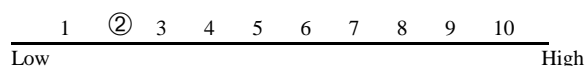
- A market needs to be developed. A battery with adequate range is critical. Cost, reliability, and performance are key for acceptability to buyers.

Ecological Risk



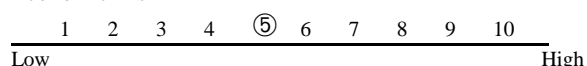
- Ecological risks are low, but battery recycling must be addressed. The system in place recycles ~98% of lead acid batteries. Other recycling systems for various advanced batteries are scarce and must be perfected.

Human Health Risk



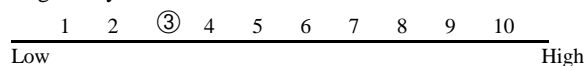
- Human health risks are almost nonexistent for these technologies.

Economic Risk



- Significant capital investment will be required by the automobile manufacturers to introduce these technologies. Continued research will be required to make them cost-effective. It may take many years for any auto manufacturer to gain a return on its investment in these technologies.

Regulatory Risk



- Regulations may be required to encourage and promote battery recycling.

Key Federal Actions

- Continuation of industry/government partnership to develop HEV, EV, and fuel cell technologies.
- Incentives for advanced vehicle purchases, including tax credits, preferential parking, and freeway lane access; reduced electricity rates for EV charging; and purchase discounts.
- Government mandates on vehicle production are a powerful incentive to commercialization although they risk damage to consumer acceptance if technologies are forced into the market prematurely.

3.4 ALTERNATIVE FUEL VEHICLES

Technology Description
<p>Alternative fuels include compressed and liquefied natural gas, biomass ethanol, liquefied petroleum gas, biodiesel, and dimethyl ether. The real leverage in carbon reductions comes from the use of biomass-derived fuels—ethanol, biodiesel, and dimethyl ether. When biomass ethanol is used purely as a blending agent with gasoline (up to at least 10% by volume, and possibly higher), no changes in vehicle technology are needed.</p> <p>System Concepts</p> <ul style="list-style-type: none"> • Alternative-fuel vehicles (AFVs) are similar to today’s vehicles, except for certain fuel- and emission-related systems. • Alcohol vehicles require corrosion-resistant fuel lines and fuel tanks, modified fuel injectors, and modified engine lubricants. • Gaseous-fuel vehicle fuel system components include fuel regulators, air and fuel mixing apparatus, and modified fuel injectors. Fuel tank modifications are also required. <p>Representative Technologies</p> <ul style="list-style-type: none"> • Flexible-fueled vehicles are available from the three major domestic automobile manufacturers. • Several models of compressed natural gas and liquefied petroleum gas vehicles are offered by automakers. • Heavy-duty alternative-fuel engines are offered as options to the commercial market for trucks and buses. <p>Technology Status/Applications</p> <ul style="list-style-type: none"> • Light-duty AFVs have shown superior in-service emissions performance and similar levels of fuel economy in federal fleet demonstrations. AFV purchase costs vary significantly depending on the fuel. Flexible-fueled vehicles have been purchased at prices below those of conventional cars, while compressed natural gas vehicles can cost \$5K more than conventional vehicles. • Heavy-duty AFVs have shown dramatic reductions in particulate emissions, with fuel economy near their diesel counterparts. Maintenance costs are higher but will decrease with experience. Alternative-fuel engines should be no more expensive, but high-pressure tanks will raise overall costs somewhat.
Current Research, Development, and Demonstration
<p>RD&D Goals</p> <ul style="list-style-type: none"> • Develop light- and heavy-duty engine and fuel technologies to meet future emissions standards. • Develop technologies that use alternative fuels in conventional vehicles with full range and performance characteristics by 2004. • By 2011, develop automotive technologies that use non-petroleum-based fuels and achieve near-zero emissions while obtaining 100 mpg in lightweight vehicles. <p>RD&D Challenges</p> <ul style="list-style-type: none"> • AFVs must be developed to meet cost, performance, and future environmental and energy efficiency goals over the lifetimes of the vehicles. Specific areas of concern include cost, range, and refueling convenience; cold-start performance and engine efficiency of alcohol fuels; and fuel-injection and storage systems for dimethyl ether. <p>RD&D Activities</p> <ul style="list-style-type: none"> • The three U.S. automakers have significant ongoing R&D programs, and several vehicle models are available today. * With DOE cofunding, heavy-duty engine manufacturers have major alternative-fuel engine R&D efforts. • Component manufacturers, national laboratories and research institutions, universities, and state and local governments have sizable alternative-fuel R&D operations. • The DOE AFVs funding levels for FY 1996 and FY 1997 were \$29M and \$26.3M. <p>Note: Fuel production and distribution research is discussed in Renewable Energy technology pathway 8.7, “Biomass Transportation Fuels” and hydrogen production and distributing is discussed in cross-cutting technology pathway 10.2, “Hydrogen.”</p>
Recent Success
<ul style="list-style-type: none"> • Work on the first-generation ultra-safe and ultra-low emission school bus powered by compressed natural gas has been completed and the bus is now commercially available. More than 100 have been sold in California, and work on the second generation is under way to improve engine efficiency and lower emissions even further. • Honda has obtained ultralow emission vehicle certification for a compressed natural gas automobile.

Commercialization and Deployment

- Domestic automobile manufacturers have been producing AFVs since 1991. Today, 11 light-duty and 19 medium- and heavy-duty vehicle models are available, powered by a number of alternative fuels. The configurations used include flexible-fuel, dual-fuel, and dedicated. Prices for flexible-fuel vehicles have decreased to those of their conventional counterparts. AFV conversion companies are successfully filling any market voids left unoccupied by domestic automakers.
- DOE and GSA are working under an interagency agreement to manage the Federal Light Duty Alternative Fuel Vehicle Project.
- The federal fleet currently contains ~33,000 light-duty AFVs. Since its inception in 1991, the DOE-sponsored alternative-fuel, heavy-duty truck demonstration program has assisted in placing more than 300 heavy-duty data collection AFVs.
- The DOE Clean Cities Program actively enables deployment of AFVs through its locally-based government/industry partnership.
- AFVs are projected to number 400,000 light- and heavy-duty vehicles by the end of 1997 in the United States.

Potential Benefits and Costs

Carbon Reductions

2010	2020	2030
2–10 MtC	4–12 MtC	15–30 MtC

RD&D Expenditures

- FY 1998 DOE RD&D budget for this pathway if \$18M.
- Annual DOE RD&D budget required for this pathway: 2000–2010, \$50M; zero in the outyears.

Market

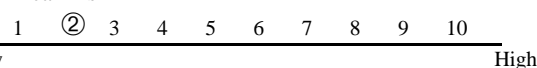
- The domestic market size for AFVs alone is between 300 MtC/year in 2010 and 400 MtC/year in 2030.

Nonenergy Benefits and Costs

- Deployment of alternative fuels may result in reductions in emissions of NO_x, CO, hydrocarbons, and fine particulates, yielding improvement in urban air quality.

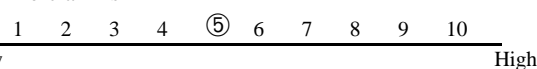
Risk Factors

Technical Risk



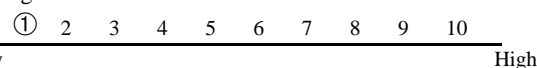
- Most of the alternative fuels RD&D is based on modifications to existing vehicle technology, and first-generation vehicles are already in commercial production.

Commercial Risk



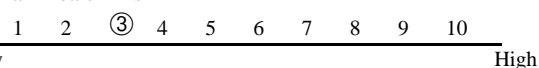
- Commercial success depends not only on cost-effective technical solutions, but also on the creation of infrastructure to produce and supply the alternative fuels.

Ecological Risk



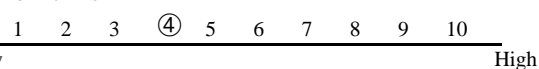
- Alternative fuels are environmentally superior choices to petroleum-based fuels. The stable of alternative fuels includes those that can substantially reduce emissions of toxics, ozone precursors, particulates, and GHGs.

Human Health Risk



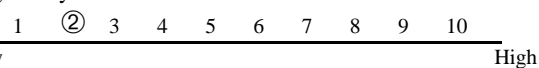
- Alternative fuels are superior to petroleum-based fuels in terms of human health risks from their manufacture, distribution, and use. The agricultural production risk impact on human health is greater.

Economic Risk



- Investment in developing these vehicles is moderate, but the large-scale investment required for the infrastructure to deliver the fuels is still a concern.

Regulatory Risk



- Alternative fuels for which vehicles are being developed are being used on a large scale. The vehicles themselves are being demonstrated, and in most cases the first generation is commercially available.

Key Federal Actions

- Vigorous implementation of current federal mandates (e.g., EPAct) could be pursued. Federal RD&D activities would contribute to development of vehicle technologies that can realize the inherent environmental and energy efficiency benefits offered by alternative fuels. Regulatory and/or tax reforms that reward alternative fuels for these benefits would increase demand for these vehicles. Vehicle cost reductions could also be pursued through continued RD&D. Finally, federal investment in fuel supply infrastructure would help alleviate fuel/vehicle, chicken-and-egg conundrum.

3.5 AIR AND HIGH-SPEED GROUND TRANSPORT

Technology Description

Carbon emissions from commercial jet aircraft can be cut through reduced drag, improved fuel combustion, and reduced idling. The National Research Council has set as a “reasonable goal” for new commercial aircraft a reduction in fuel burn per seat mile of 40% compared with current airplanes. Of the total 40%, 25% is expected from improved engine performance and 15% from aerodynamic and weight improvements. Electrified high-speed ground transportation modes (speeds > 150mph) can reduce carbon emissions by diverting trips from conventional fossil-fueled modes and by using more efficient suspension and propulsion system technologies. Since high-speed rail (HSR) and maglev systems derive their power from the utility grid, potential carbon reductions are directly linked to electric generating technology efficiencies and carbon emissions. Passengers are emphasized here, but technologies also apply to cargo.

System Concepts

- HSR (speeds of up to 200 mph) uses locomotive-drawn coaches supported by steel wheels on steel rails. Single-phase power is transformed from transmission-line voltages at substations, distributed along the right of way, and delivered to locomotives via catenary-pantograph systems, where it is converted by power conditioning equipment to voltages and frequencies needed by the propulsion motors. Regenerative braking systems can be used but generally require energy storage.
- Maglev is a new mode of high-speed (up to 300 mph or more) guided ground transportation that uses magnetic forces for non-contact support, guidance, propulsion and braking. Most of the power conditioning equipment and propulsion system is at wayside, making the vehicles much lighter and automatically controllable.
- Propulsion efficiency in aircraft can be increased by still higher turbo-fan bypass ratios, increased cycle pressure ratios, higher turbine inlet temperatures, improved turbine aerodynamics, and lighter engine parts. The most promising approach for reducing drag appears to be methods for increasing laminar flow next to the surface of aircraft, but turbulence control and reduction in induced drag also can help improve lift-to-drag ratios. A 1% reduction in empty aircraft weight can reduce fuel consumption by 0.25% to 0.50%. Maximum use of lightweight, high-strength materials could conceivably increase non-metallic content of aircraft to a maximum of about 80%, with an overall 30% reduction in weight.

Representative Technologies

- Existing HSR systems include the French TGV, German ICE, and Japanese Nozomi. All require electrified railways. Possible enhancements and alternatives include use of on-board energy storage devices and high-temperature superconducting components. Locomotive designs using advanced prime movers such as fuel cells and high-efficiency gas turbines could conceivably compete with electrified systems for speeds up to about 150mph, but market and emission benefits would be less.
- Foreign maglev technologies: the German Transrapid (conventional electromagnet, attractive-force system); the Japanese Linear Motor Express (superconducting magnet, repulsive-force system).
- Ultra-high bypass turbofans, increasing bypass ratios up to 10.
- Propfan technology with advanced, counter-rotating prop designs.
- Lightweight, high-strength structural and surface materials.
- Advanced computational fluid dynamics for engine and airframe design.
- Hybrid laminar flow control technology for drag reduction.

Technology Status/Applications

- HSR is a mature technology in several foreign countries, and it is not likely that the United States could compete. Hence, the benefits would derive from implementing that technology in the United States and diverting passengers and cargo from fossil-fueled modes.
- The German Transrapid was certified for application in 1991. Full-scale testing of the Japanese superconducting system on the Yamanashi Prefecture test line is scheduled to be completed in 1998.
- Foreign maglev technologies are expensive and have other characteristics that may limit their applicability in the United States.
- Foreign competition is driving new aircraft and engine designs by Boeing, NASA, GE, and Pratt & Whitney.
- Advanced aircraft technologies are under development by NASA, Boeing, and engine manufacturers.
- Propfan technology has been demonstrated but could benefit from cost reduction and noise and vibration improvements.
- Aspects of laminar flow control have been demonstrated in limited tests, but a practical system has not yet been developed.

Current Research, Development, and Demonstration

RD&D Goals

- For speeds of 90 to 150 mph, the DOT/FRA Accelerail Program focuses on passenger rail technologies that can use existing railroad rights of way (mainly owned by the freight railroads).
- Implement electrified HSR systems where commercially viable.
- Develop and test concept of innovative domestic maglev system designs within the next 2 years; refine designs and performance testing within the following 2 years; design and initiate demonstration projects in the following 2 years.
- Develop room-temperature maglev (LLNL contract with NASA to develop its Inductrack System).
- Achieve 40% overall efficiency improvement in new aircraft by 2025, 25% propulsion efficiency improvement, and 15% efficiency gain from drag and weight reduction.

RD&D Challenges

- Meet or exceed performance of foreign maglev systems at reduced construction costs. Develop manufacturing techniques and lightweight, strong, inexpensive materials for vehicle and guideway components.
- Develop suspension and propulsion system components that will meet the higher performance and lower cost requirements.
- Develop efficient, reliable superconducting magnet designs.
- Reduce NO_x emissions while increasing turbine cycle temperatures and pressures for thermodynamic efficiency.
- Develop a low-cost, low-maintenance, low-noise and -vibration propfan so that airlines will demand their installation on new aircraft.
- Develop a hybrid laminar flow control system that is practical and maintainable under real world operating conditions (e.g., dust, insects).
- Lower the cost and improve the manufacturability of high-strength, lightweight, non-metallic materials for engines and airframes.

Current Research, Development, and Demonstration (continued)

RD&D Activities

- Design and test maglev system components.
- Develop supporting technologies such as high-temperature superconductors, composite materials, power electronics, zero- or low-carbon-emitting electric power generating technologies.
- Design transportation systems together with incentives that incorporate maglev and HSR systems cost-effectively and that divert as many trips as possible from privately owned vehicles and short-haul aircraft.

Recent Success

- New HSR technology has increased the top speed for commercial operation to 200 mph in France. Development of German and Japanese maglev and HSR has been highly successful. Four innovative maglev system designs were developed under the auspices of the NMI.
- High bypass turbo-fan on Boeing 777, advanced propfan able to achieve Mach 0.7, numerous advances in laminar flow control, and adoption of drag reduction via riblets and winglets on several commercial aircraft.

Commercialization and Deployment

- Construction on the first commercial route of the Transrapid system (Hamburg to Berlin) is scheduled to begin in 1998. The Japanese will reach a decision on commercialization by the year 2000. Deployment of existing maglev technology in the United States could begin with small pilot projects to introduce the technology and demonstrate its benefits and ability to attract financing.

Potential Benefits and Costs

Carbon Reductions

2010	2020	2030
7–12 MtC	15–30 MtC	25–50 MtC

RD&D Expenditures

- Current NASA RD&D budget for energy-efficient aircraft is \$175M/year.
- Annual federal RD&D budget required for this pathway: 2000–2030, \$300M/year.

Market

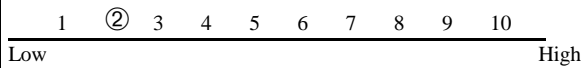
- From 85 MtC/year (2010) to 150 MtC/year (2030).

Nonenergy Benefits and Costs

- Maglev and to a lesser extent HSR: reduction of urban air pollution, highway and airport congestion, freeing of airport slots for more efficient long-haul and international flights, increased mobility, increased energy security.

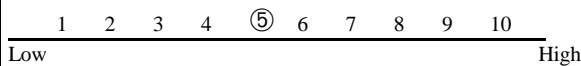
Risk Factors

Technical Risk



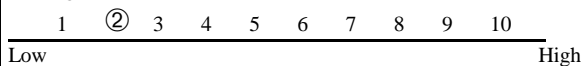
- Japanese and German maglev is near the application stage. Some risk is involved in developing domestic maglev options until testing and demonstration is completed.

Commercial Risk



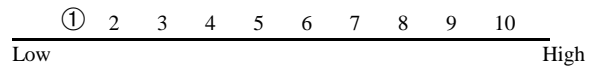
- Commercial risk can be mitigated by developing two or three well-designed pilot projects with the support of partnerships involving federal, state, and private financing. Short-haul airlines could be significantly impacted in HSR and maglev corridors.

Ecological Risk



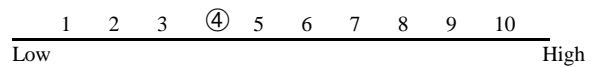
- Electrified HSR and maglev systems are relatively environmentally friendly compared with conventional trains and aircraft. Elevating tracks reduces ecological risk further.

Human Health Risk



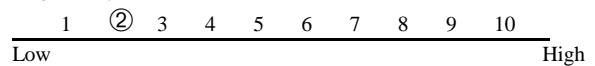
- There are no local emissions and magnetic field exposure does not pose a human health risk.

Economic Risk



- Ridership base for high speed rail is uncertain.

Regulatory Risk



Key Federal Actions

- Establish an RD&D program for next-generation maglev technology in the United States. Identify and fund supporting technologies. Use the existing MOU with DOT.
- Establish a program to demonstrate existing technology through two or three revenue-earning pilot projects, each of about 40 miles.
- Provide leadership for the formation of public/private partnerships to finance and operate such projects. Incorporate programs into NEXTEA legislation. Request and support legislative actions to appropriate funding for programs.

Energy-Efficient Technologies

4. Agriculture and Forestry

4.1 Conversion of Biomass to Bioproducts

4.2 Advanced Agriculture Systems

4.3 Plant/crop Engineering

4.1 CONVERSION OF BIOMASS TO BIOPRODUCTS

Technology Description
<p>Annual crops, perennials, and short-rotation woody species represent plant/crop-based resources that are a renewable source material in the food, feed, and fiber industries. The current market of biobased materials exceeds 85 million tons/year. The use of such biobased processes to produce materials and products provides a modest but significant reduction in GHGs by two measurable effects. First, lowering the use of petroleum-based feedstocks reduces the inherent emissions associated with these feedstocks, since biobased products are synthesized from ambient CO₂ currently in our atmosphere. Second, the use of biobased processes has shown some potential for emitting roughly the same, or in some cases fewer, GHG emissions as petroleum-based processes.</p> <p>System Concepts</p> <ul style="list-style-type: none"> • The United States has significant forestry or plant/crop-based resources, including forestry, rangeland, and a highly productive agricultural system. In the past 50 years, these resources have been largely focused toward food, feed, and fiber production. • Use of forestry/crop resources for energy, or as basic building blocks for industrial production, has been limited because of a poor fit with the current hydrocarbon processing system. However, this is not an either/or system choice. • The concept being proposed involves developing manufacturing platforms employing the uniqueness of biobased materials to provide society's materials needs or integrated manufacturing platforms that overcome the poor fit scenario described earlier. <p>Representative Technologies</p> <ul style="list-style-type: none"> • New biotechnologies for plant growth and production and biotechnology and benign chemical synthesis for conversion of biomass materials into products. <p>Technology Status/Applications</p> <ul style="list-style-type: none"> • Corn wet-mills, pulping operations, and dimensional lumber facilities represent a significant segment of the industrial community. All are cost-effective. What is not cost-effective or is poorly implemented is the development of broader economic platforms based on forestry/crop-derived inputs. DOE and other federal agencies have been applying their technologies to the development of these new manufacturing options.
Current Research, Development, and Demonstration
<p>RD&D Goals</p> <ul style="list-style-type: none"> • It is more suitable in this pathway to outline directional goals (i.e., goals that outline a direction rather than an end point). • To implement at least 10% of basic chemical building blocks arising from plant-derived renewables by 2020 with development concepts in place to increase this to 50% by 2050. • To develop economically viable manufacturing platforms for selected products (such as plastics, textiles, cosmetics) by 2020 using plant-based (crop, forestry, processing) systems that produce renewable feedstocks. • To build collaborative partnerships among industrial stakeholders, growers, producers, academia, and federal/state governments to develop small- to large-scale commercial applications such that the distinction between processing biobased materials for food, feed, and fiber and the manufacturing of basic materials will begin to disappear. <p>RD&D Challenges</p> <ul style="list-style-type: none"> • There are three major challenges in establishing these biobased manufacturing platforms: <ul style="list-style-type: none"> — Using forestry/agriculture-based inputs in modified but existing processing systems. — Developing new or modified forestry/agriculture-based plant/crop production systems to provide desirable feedstocks. — Integrating these approaches to create optimized systems that generate these new economic platforms based on the use of biomass-derived inputs. • What is needed is a larger suite of viable examples to demonstrate the potential for a renewables-based approach. There is simply not enough available technology to establish an even larger role of forestry/agriculture-based products and materials, especially in benign organic syntheses, biotechnology, and new materials development. <p>RD&D Activities</p> <ul style="list-style-type: none"> • DOE's OIT is leading the effort in producing biobased products. The FY 1996 and 1997 budgets were about \$8.4M and \$3M, respectively. The USDA's Agricultural Research Service (ARS) and the Cooperative State Research Extension and Education Service (CSREES) also are engaged in similar work. The ARS budgets in FY 1996 and FY 1997 have been about \$20M/year (exclusive of their effort in ethanol). The CSREES effort in FY 1996 and FY 1997 spent about \$3.5M/year. Industry is sponsoring work. Although the exact numbers are not available, two examples provide some idea of magnitude. Genencor and Eastman Chemicals are pursuing a \$30M/5 year 50:50 cost-shared project with the NIST/ATP program to develop biocatalysts for chemical processing. DuPont has announced an effort in biological production of 1,3 propanediol from corn syrup as a precursor to new polymers. This is one of several efforts by industry.
Recent Success
<ul style="list-style-type: none"> • Citric acid is an acidulent used in food processing and was produced by fermentation using paraffin oils from petrochemical sources until the 1980s. Currently, this 300 million lb/year commodity chemical is produced solely and economically from fermentation of corn syrup. The rayon fabric and cellophane packaging market is based solely on wood and is commercially viable. Recently, the production of high-fructose corn syrup from corn starch for food sweeteners has become a commodity market with more than 12 billion lb produced annually.

Commercialization and Deployment

- The current, annual U.S. production market for biobased products and materials is more than 85 million tons. At an average value of \$0.25–0.50/lb, the total annual sales are between \$45B and \$85B. The major manufacturers are the pulp/paper, grain processing, and food processing industries. The concept is the development of new manufacturing platforms compatible with the market drivers, and, where appropriate, integrated with existing chemical, forestry, and agricultural manufacturing operations. There is no attempt to replace efficient hydrocarbon processing, but rather to develop alternative processing capabilities to establish new manufacturing platforms. This involves a paradigm shift, not a battle over competing technologies. Critical challenges to widespread deployment are noted under RD&D challenges.

Potential Benefits and Costs

Carbon Reductions

- 2–5 MtC/year 2010
- 10–15 MtC/year 2020
- 15–25 MtC/year 2030

RD&D Expenditures

- Federal RD&D funding requirements for this pathway: \$25–50M/year through 2010
- \$50–75M/year through 2020
- \$10–15M/year through 2030 (should be essentially market driven by then).
- Because of the limited number of examples to demonstrate commercial viability, substantial federal funds are necessary through the year 2020.

Market

- The major contributors to the carbon reduction values noted are reductions related to the displacement of petroleum typically used to manufacture products. In addition, if cogeneration of energy were employed in biomass-based manufacturing analogous to the pulping industry's use of biomass as a fuel, additional energy savings could be achieved. These cannot be calculated exactly but can be estimated. For example, processing energy for chemicals amounts to about 3 quads of energy. If biobased materials processing involved cogeneration of power analogous to the forestry industry (50%) on 10% of the chemicals volume, then purchased energy could be reduced by about 0.15 quads, reducing net GHG emissions.

Nonenergy Benefits and Costs

- This technology involves developing new manufacturing platforms and not displacing petrochemical platforms. It would lead to development of a new mode of operation within existing infrastructures or development of altogether new infrastructures.

Risk Factors

Technical Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- Much technical information is available, but there are limited numbers of applied technologies.

Commercial Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- Very limited number of examples to demonstrate full commercial viability.

Ecological Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Technologies for conversion of biomass to products generally produce fewer negative environmental impacts than do traditional production processes.

Human Health Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Farming and agriculture have low human health risks. Chemicals production has slightly higher risk factors.

Economic Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- If successful, the technologies would strengthen the economy and create American jobs.
- Generally perceived as a “green technology” by the public.

Regulatory Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Qualifying bioproducts from biomass for use in commercial manufacturing carries some regulatory risk, but the industries involved are well versed in this area.

Key Federal Actions

- Establish a federal RD&D program to develop improved conversion technologies for agricultural/forestry products, and develop viable and economic examples of biobased-product manufacturing technologies.
- * Establish stronger interagency and federal agency–industry partnerships with increased involvement with suppliers of feedstocks represented by professional agriculture and forestry societies, cooperatives, and ecological interest groups.

4.2 ADVANCED AGRICULTURE SYSTEMS

Technology Description
<p>Advanced agriculture systems enable a process of collecting and using increasingly detailed site-specific information in conjunction with traditional farm management tools such as agronomy, machinery, finance, and marketing for accessing and applying the best available information to better manage individual farming operations. In addition, these systems provide for improved understanding, control, and, perhaps, manipulation of microbial processes at plant roots and in soils to control flows of carbon and nitrogen. These systems provide an integrated capability to improve environmental quality while enhancing economic productivity by increasing energy efficiency, optimizing fertilizer and other chemical applications, and conserving soil and water resources.</p> <p>System Concepts</p> <ul style="list-style-type: none"> • Global positioning infrastructure and remote and in situ sensors for soil, crop, and microclimate characterization. • Cropping system models, data and information analysis, and management tools. • Variable rate application control systems and smart materials for prescription delivery. • Biological and chemical methods for manipulating microbial processes to increase efficiency of nutrient uptake and to suppress GHG emissions. <p>Representative Technologies</p> <ul style="list-style-type: none"> • Global positioning satellites and ground systems, and satellite- and aircraft-based remote and in situ electrical, magnetic, optical, chemical, and biological sensors. • Advanced artificial intelligence and information networking technologies; autonomous control and robotics systems; and soil, crop, moisture, pest, and microclimate responsive (smart) materials. • Biological and chemical methods for microbial process manipulation. <p>Technology Status/Applications</p> <ul style="list-style-type: none"> • Many first-generation precision agriculture technologies are available for application and are in use on ~10% of U.S. farms. • Information management and networking tools; rapid soil characterization sensors; selected crop stress, yield, and quality sensors; and a systematic integration of all technologies for all major cropping systems are not yet at technical performance levels required for application. • Strong understanding of soil microbes and relationships exists in the agriculture, energy, and university research community. • Capability exists to develop smart materials and methods for microbial manipulation.
Current Research, Development, and Demonstration
<p>RD&D Goals</p> <ul style="list-style-type: none"> • Technologies that improve production efficiencies and reduce energy consumption by 4% by 2010, 16% by 2020, and 39% by 2030. • Remote and field-deployed sensors/monitors and information management systems for accurate, real-time monitoring and analysis of crops, soils, water, fertilizer, and agricultural chemicals use/efficiency to meet the fertilizer and energy reduction goals. • Smart materials for prescription release: four to five main crops by 2010 (10 chemicals); 20 crops by 2020; and all important crops by 2030. • Advanced fertilizers and technologies to improve fertilizer efficiency and reduce nitrogen fertilizer inputs by 20% by 2020. • Methods of manipulating microbial processes to materially increase the efficiency of nitrogen uptake and suppress CO₂ emissions. • Initial systems models and prototype operation by 2000 on selected cropping systems that are major contributors to U.S. food and fiber use and export. • Deployment of first-generation integrated system models, technology, and supporting education and extension infrastructure by 2002. • Complete transition of first-generation system development to the private sector by 2004. <p>RD&D Challenges</p> <ul style="list-style-type: none"> • Site-specific agriculture in general requires advances in rapid, low-cost, and accurate soil nutrient and physical property characterization; real-time crop water need characterization; real-time crop yield and quality characterization; real-time insect and pest infestation characterization; autonomous control systems; and integrated physiological model and massive data/information management systems. • Smart materials that will release chemicals based on soil and crop status depend on modest breakthroughs in materials technology. • Improved understanding of specific soil microbial processes is required to support development of methods for manipulation. • Models that represent accurate understanding of plant physiology must be coupled with models that represent soil processes such as decomposition, nutrient cycling, and water storage and flows to understand how ecosystems respond to atmospheric change. • Detailed and simultaneous examination of biogeochemical reactions that occur in near-surface groundwater is required to improve understanding of nutrient cycling, GHG concentration, and degradation of contaminants. • Improved understanding of the pathway by which nitrate is reduced to gaseous nitrogen is required to support scaling of emissions estimates associated with the nitrogen cycle. • The microecological consequences of expanding carbon stock in soils resulting from suppressing CO₂ emissions are unknown or uncertain. <p>RD&D Activities</p> <ul style="list-style-type: none"> • Complementary efforts are under way in both public and private sectors. • Sponsors include USDA, DOE, NASA, universities, state agencies, commodity groups, and sensor and satellite developers; the principal funding comes from USDA. • Current funding level provided by U.S. government sponsors is estimated at \$40M.
Recent Success
<ul style="list-style-type: none"> • High-resolution satellite imagery can be used to identify stress and disease in some crops at 1-to-2 m resolution. • Research programs have related reflectance spectra to disease or nutrient status. • Technology was developed to coextrude recyclable plastics with ammonium polyphosphate for continuous ammonium release in the presence of water. • Research programs have demonstrated performance of microbially encapsulated fertilizer. • Rf-link deployable field sensors exist for ground moisture monitoring. • Commercial sensors exist for CO₂ and ammonia gas monitoring and for accurate yield monitoring of grain and tuber crops.

Commercialization and Deployment

- Global positioning systems, geographic information system software for parameter mapping, remotely sensed imagery, selected yield monitors, and selected variable rate control systems for seed, fertilizer, and chemical applications are commercialized and in application in the United States, Canada, Australia, and Europe.
- Slow-bleed release pesticides are available commercially.
- No commercial methods for microbe manipulation are available.
- Current traditional agricultural inputs (seed, fertilizer, chemicals), monitoring systems, and non-site-specific application equipment are competing technologies.
- The infrastructure in place for agricultural production will support these technologies with little change; however, the cost to compete with other technologies may initially be high until technology integration is complete.

Potential Benefits and Costs

Carbon Reductions

- 1–2 MtC/year by 2010, 5–10 MtC/year by 2020, 15–20 MtC/year by 2030

RD&D Expenditures

- Federal funding of \$80M to \$120M/year, equivalent to 2 to 3 times current expenditures, is needed through 2030.

Market

- Development and scheduling of delivery systems for water and nutrients. For example, injecting rather than broadcasting nitrogen on no-tillage corn can reduce nitrogen use by 35% to 59% and reduce costs by \$5 to \$20/acre.
- Market for technologies exists not only in the United States but worldwide. In developing countries dependent on agriculture, the market for improved agricultural systems is substantial.

Nonenergy Benefits and Costs

- Petroleum consumption reduction of 4% through 2010; 16% through 2020; 39% through 2030.
- Enhanced economic productivity while maintaining sustainable production to meet rapidly escalating international food, fiber, alternative feedstock and renewable energy demands, improved soil fertility, improved environmental quality.

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Durability, shelf life, field life, yields, and reaction rates are issues.
- Not clear whether materials can be manufactured that are both appropriately sensitive and deployable.

Commercial Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Sensors are expensive, and it has not been demonstrated that they can be manufactured cheaply and in large quantities.
- Many unit processes and components already exist.
- Power sources and property rights to processes and microbes are issues.
- Industry has little experience manufacturing smart materials and may require some infrastructure changes to accommodate these.
- Manufacturing or growing microbes may impose limits.

Ecological Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Potentially harmful waste streams in manufacturing and workplace environments.
- Controlling release of fertilizers and chemicals and microbes into the environment is an issue.

Human Health Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Potential health risks result from possible environmental releases described as ecological risks.

Economic Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Recycling used-up or worn-out sensors; potential annual recycling.
- Recycling used-up or worn-out substrate; plans are to make such materials from recycled material and use it multiple times.
- Society is generally averse to risks associated with genetically altered or artificially propagated microbes in the environment—concern with “superbugs.”

Regulatory Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Regulatory issues may arise from the manipulation of microbes and the introduction of genetically engineered microbes to the environment.

Key Federal Actions

- Allocate funding in sufficient quantities to support end product completion and measure performance toward specific objectives.
- Sustain a directed basic and applied research effort on sensors, information sciences, materials, and microbial processes.
- Establish a federal initiative to develop a multiagency, public/private, joint program.
- Apply systems engineering and integration disciplines to effectively develop and guide program formulation and implementation.

4.3 PLANT/CROP ENGINEERING

Technology Description
<p>Plant/crop engineering involves improving plant productivity and utility in capturing solar energy and converting it to chemical energy through traditional and functional genomics; genetic engineering; and developing transgenic plants for the purposes of increased biomass production, increased carbon fixation, improved nitrogen utilization and recycling, and biomass conversion technologies. DOE has invested significantly in understanding energy conversion technologies, hence bringing to bear a significant resource to this most basic of energy storage and conversion needs.</p> <p>System Concepts</p> <ul style="list-style-type: none"> • Plant genomics: development of genomic maps for detailed studies of genomes, genes, and genetic processes. Traditional genomics includes gene mapping, molecular cloning, large scale DNA sequencing, data management and computational analysis. Plant genomics is necessary for the development of new or improved crop and forest species that promote sustainability and profitability of plant production and improvement of quality. • Photosynthetic efficiency: physiological and genetic control of photosynthetic pathways for efficient sunlight capture and conversion to biomass. • Nitrogen fixation and metabolism: genetic control of nitrogen cycling and nutrient use efficiency. Technologies that optimize the efficiency of nitrogen use by plants to ensure site sustainability while minimizing losses of nitrous oxide from soil. • Functional genomics for high-performance plants: using the tools of traditional genomics to focus on the structure and function of novel gene sequences from a variety of organisms. For example, functional genomics may employ biomass genotypes from extreme environments or biomass genotypes that express novel characteristics to identify and isolate novel gene sequences. • Gene expression, compartmentalization, and timing: once identified, desirable genes must be introduced successfully into target biomass species and expressed (i.e., make their product). For these genes to be useful in carbon management, technologies need to routinely accomplish stable gene insertion into host genomes, including desirable biomass species that may be difficult to transform, and to prove reliable the expression of these genes over time and in diverse environments. • Plant engineering for end use: development of new or modified plants that will enable or assist the development of breakthrough biomass conversion technologies and allow plants to serve as biological factories for production of chemicals, enzymes, materials, and fuels. <p>Representative Technologies</p> <ul style="list-style-type: none"> • Use of plant assembly fundamentals to create fast-growing tree crops that produce high-strength structural wood and composites for use in construction. • High-resolution mapping with techniques such as amplified fragment length polymorphism analysis. • Genetic transformation: the use of cellular and molecular techniques to insert a single target gene into the DNA of an organism. • In situ hybridization to determine the location of DNA sequences and genes on chromosomes. <p>Technology Status/Applications</p> <ul style="list-style-type: none"> • With more than 2100 field trials of crops under way in 1995/1996, the technology is obviously viable. However, the time necessary to develop a new plant with desired traits needs to be reduced to bring to bear the full effect of this technology. • Genetically engineered species comprised nearly 20% of the cotton crop.
Current Research, Development, and Demonstration
<p>RD&D Goals</p> <ul style="list-style-type: none"> • Increasing the ability to express cloned genes by a factor of 10 will reduce cycle time for development of new transgenic field crops from 5–10 years to 2–5 years and the cycle time for forestry cultivars from 7–15 years to 3–7 years. • Increasing the number of completed genome maps of selected plant species from zero to five in 10 years. <p>RD&D Challenges</p> <ul style="list-style-type: none"> • Plant genomics; photosynthetic efficiency improvements; nitrogen fixation and metabolism; functional genomics for high-performance plants; gene expression (compartmentalization/timing); and plant engineering for end use. Using high-resolution analytical techniques such as DOE’s Advanced Synchrotron Light Source. Employing the potential of advanced sensor technology to correlate performance properties of agriculture/forestry materials with genetic and structural composition (this is being evaluated now with some success by DOE scientists). <p>RD&D Activities</p> <ul style="list-style-type: none"> • DOE spends about \$25M annually on basic plant engineering and about \$8M annually on sustainable forestry and biomass feedstock development. USDA’s budget in their Cooperative State Research Extension and Education Service spent \$57M in 1996/1997 with an additional \$11M in global change R&D. The Agricultural Research Service spent about \$30M.
Recent Success
<ul style="list-style-type: none"> • Transgenic cotton resistant to the boll weevil comprised 2.5 million acres of 14 million acres planted in 1997. The following genetic traits have been engineered into plants that are now reaching the commercial market: insect, virus and herbicide resistance, specialty oils, slower ripening, and increased pectin.

Commercialization and Deployment

- Fractions of major crops (15–20% of soybean, cotton, corn) are being planted with transgenic seeds. Industrial funding is significant, with a seed market sales projection of \$6 billion in 2005. Increased use of both conventional and hybrid plants (alfalfa, wood wastes, bagasse, willow), for energy production is nearing commercial reality. Forestry and agricultural crops bred for energy use are currently being evaluated. Major seed and agrichemical companies are involved in agricultural systems along with USDA and farmers. Forestry issues are being studied by DOE and USDA. A critical challenge to widespread deployment is economics. The freedom-to-farm capability may drive more development in plant/crop engineering.

Potential Benefits and Costs

Carbon Reductions

- Because of the strong interdependency of plant engineering technologies, biomass conversion technologies, and advanced agricultural systems, carbon reductions are incorporated into reductions reported for biomass conversion technologies and advanced agricultural systems pathways.

RD&D Expenditures

- Most R&D activities will require federal funds, especially initially until sufficient field data exists to verify technology.
- Current annual federal expenditures exceed \$130M.
- Annual federal RD&D budget required for this pathway: to 2020, \$155M/year; 2020 to 2030, \$140M/year.

Market

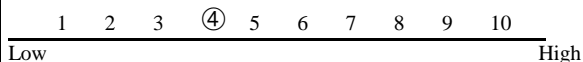
- For energy production derived from biomass, the current 2–4 quads of energy produced could be impacted by a reasonable fraction with plants engineered for energy production uses (increase in lignin, decrease in alkali salts, etc.). This displaces currently heavy coal dependence. For biomass to bioproducts, the impact would be to reduce oil imports needed to synthesize organic chemicals. The realistic goal is a displacement of about 1 quad of energy embodied in petroleum feedstocks.

Nonenergy Benefits and Costs

- Development of crop plants with improved properties such as nutritional quality and extended storage life.

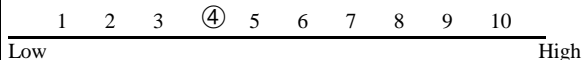
Risk Factors

Technical Risk



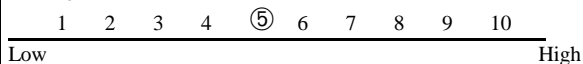
- Unproven technology with minimum of field data.

Commercial Risk



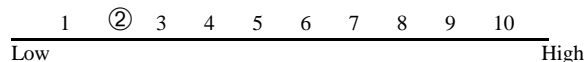
- Historic precedent in developing hybrid plants/trees has been very successful.
- Infrastructure for developing new techniques exists.

Ecological Risk



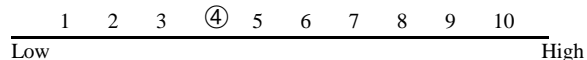
- May increase ecological advantages, but life-cycle impacts will need to be studied.

Human Health Risk



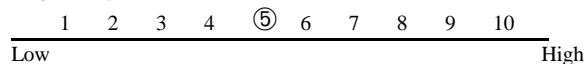
- Plant research is generally very benign.

Economic Risk



- Public often perceives genetically engineered organisms as a threat. Alterations of pathways often can be defeated by the plants themselves.

Regulatory Risk



- Once new transgenic plants show value, these risks will diminish. The converse is true. If problems arise, regulation will remain.

Key Federal Actions

- Increased support to resource-intensive but beneficial efforts such as sequencing of plant genomes. Increased support to DOE's efforts in relating plant engineering to energy applications.

Clean Energy Technologies

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 Carbon Dioxide for Improved Oil and Gas Recovery

5.1 ENERGY EFFICIENCY FOR CRUDE OIL REFINING

Technology Description

Refining of petroleum crude oil remains a dominant and strategic industry for the U.S. economy. Refining involves separating and converting crude oil hydrocarbon stocks to produce transportation fuels such as gasoline, kerosene, and jet fuel and by-product fuels such as petroleum coke. Separation and conversion processes used in refineries are energy intensive; the source of energy is often the combustion of light hydrocarbon gases that produce CO₂. Fugitive emissions of light hydrocarbon gases from refining operations are another source of GHGs.

System Concepts

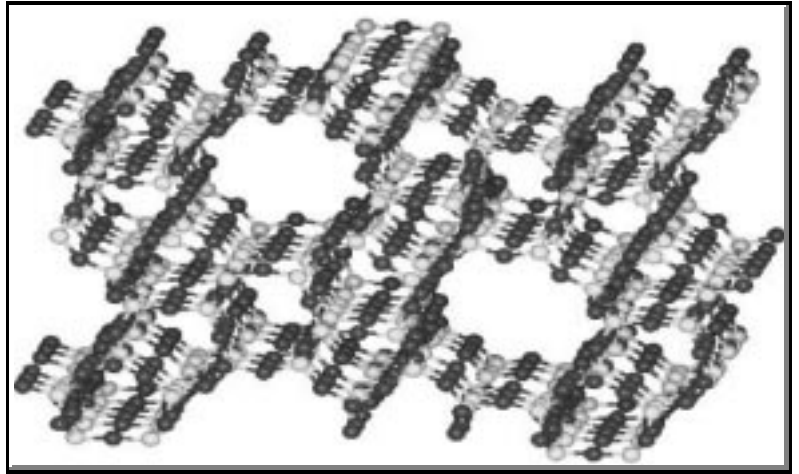
- Hydrocarbon use can be made more efficient by increasing the efficiency of converting crude oil to transportation fuels and/or separating and using valuable components of refining off-gases (light hydrocarbons). The former leads to higher yields, and the latter prevents useful off-gases from entering a combustion stream.
- Reducing the amount of low-value product (such as fuel grade coke) increases the efficiency of the refining process.
- Several refining processes produce off-gases that have value if they can be separated.

Representative Technologies

- Catalysis improvements
- Advanced separation methods (membranes)
- Mild pretreatment processes
- Refinery process optimization and advanced sensors

Technology Status/Applications

- Energy-intensive distillation and other conventional separation processes are still the workhorses of the refinery. However, these suffer in separation efficiency and downtime.
- Energy-intensive steam reforming of methane to synthesis gas followed by methanol synthesis is still uneconomical.
- Heavy oil upgrading process efficiency has plateaued.
- Optimization modeling technology for refining systems is moving toward technologies such as reactive multiphase flow simulations.



Zeolite ZSM-5 catalyst structure

Current Research, Development, and Demonstration

RD&D Goals

For the near term:

- Demonstrate new refinery catalysts with improved efficiencies and selectivities.
- Test fugitive gas emission identification techniques (tracers and backscatter imaging equipment) in refinery settings.

By 2003:

- Demonstrate on a pilot scale that advanced inorganic membranes can be used to separate and use refinery off-gases.
- Demonstrate on a pilot scale that heavy oil processing can be improved by pretreating to remove impurities before catalytic upgrading.
- Laboratory test short-contact-time reactors with higher methane conversion and greater carbon selectivity.

By 2008:

- Demonstrate through simulations how a combination of advanced sensors, detailed modeling, and process optimization could lower emissions and improve energy efficiency.

RD&D Challenges

- To effectively use off-gases, advanced separation methods must be developed. Inorganic membranes offer promise in this area. Membranes made from zeolites, sol-gels, aerogels and combined zeolites-sol-gels offer the potential of tailor-made separation materials (i.e., hydrogen from nitrogen or isolation of methane). With the proper inclusion of different types of metals in these porous materials, olefins from alkanes could also be separated.
- Specific target catalysis areas are alkylation processes, catalytic cracking, heavy oil cracking, and hydrocracking.
- Up to 50% of heavy oil is of little value to refiners because the nondistillable portion is of poor quality and is difficult to convert to transportation fuels. This material is often converted to low-grade coke. Pretreatment conversion technologies would allow more of the heavy oil to be converted to high-value, more efficiently burning transportation fuels.
- In the case of methane, for full utilization, separation must be followed by a conversion process. This conversion process would serve the same purpose as with natural gas, which is to make liquids that can be handled in a similar manner as refinery distillates.

RD&D Activities

- Supporting efforts are sponsored primarily by DOE/FE with some assistance from EE and ER. Funding is typically less than \$10M/year.
- Newer technology for methane liquifaction involves partial oxidation of methane to synthesis gas that removes the thermodynamic limitations of steam reforming. Partial oxidation followed by methanol synthesis represents a potential solution that is being researched.
- It is estimated that a methane conversion efficiency of greater than 30% with a carbon selectivity of greater than 85% is needed. These schemes will require short-contact-time reactors at elevated temperatures, some with novel methods of heating and quenching. These short-contact-time reactors will involve bed configurations in which the energy to initiate the reactions is supplied to the catalyst by chemical, radio frequency, or microwave energy.

Recent Success

- The feasibility of nitrogen-methane separation with tailored zeolite materials on glass substrates derived through the sol-gel manufacturing process has been demonstrated in the laboratory.
- The application of barrier membrane technology to separate hydrogen in several different refinery streams is being investigated. The benefit of this technology is a very-high-throughput membrane that can operate at process temperature and pressure with high separation factors.

Commercialization and Deployment

- Catalysis technology is at various levels of development, from experimental to commercial.
- With modern simulation and analysis technology, better knowledge of unit operations and integrated processes offers the opportunity for true process optimization. The scales run the gamut from molecular level simulations to continuum level analysis to systems level analysis. With improved process sensors and controls, lower emissions and more efficient energy usage can be achieved.
- 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 proved effective in imaging methane plumes at remote distances and ppm concentrations. Recent improvements in LIDAR systems for national security missions should be applicable to fugitive gases as well.

Potential Benefits and Costs

Carbon Reductions

- The petroleum refining industry consumes 5.9 quads per year, 80% of which results from burning fuels in refinery heaters and boilers.
- Improved off-gas separations, more selective catalysts, and effective methane capture could cut GHG emissions 10 to 20% in a decade. This represents a potential carbon reduction range of 8.5 to 17 MtC/year.
- Carbon reduction estimates from this pathway are 2–4 MtC in 2010, 3–6 MtC in 2020, and 4–8 MtC in 2030.

R&D Expenditures

- Current DOE RD&D funding for this pathway is approximately \$10M/year.
- Annual DOE RD&D budget required to generate the estimated carbon reductions is \$15M/year, 2000–2030.

Market

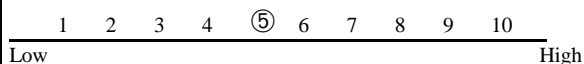
- This technology pathway is applicable to the entire refining industry.

Nonenergy Benefits and Costs

- The United States is steadily losing refining capacity. Only new technology that addresses all environmental concerns will stabilize this trend.
- The United States produces much heavy oil. An improved refining process could add \$1 to \$2/bbl to the value of this oil.

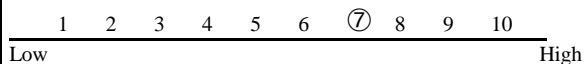
Risk Factors

Technical Risk



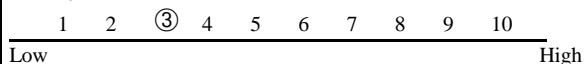
- Technologies have been demonstrated at small scale. The scale-up challenge cannot be minimized.

Commercial Risk



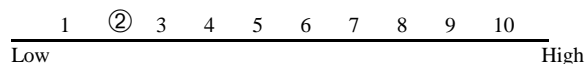
- Refineries have been leaving the United States because of environmental cleanup costs.

Ecological Risk



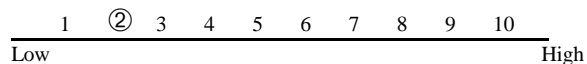
- The technology could be developed and implemented to make crude oil refining and processing facilities consistent with environmental regulations.

Human Health Risk

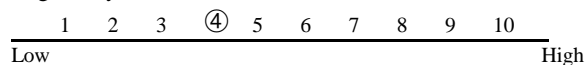


- The refinery of the future will be a vast improvement over current technology.

Economic Risk



Regulatory Risk



Key Federal Actions

- The federal government could work with the petroleum industry to allow the refining of crude oil to rebound as a high-technology, clean, strategic industry for the U.S. economy.
- Collaborative industry/government/university research efforts on catalysis, membrane separations, heavy crude upgrading, and process efficiency improvements could be increased.

5.2 NATURAL GAS TO LIQUIDS

Technology Description

Conversion of natural gas to liquids (GTL) has shown considerable advancement in the past 5 years. Novel processes for the physical conversion of gas to liquefied natural gas (LNG) in remote areas have been identified and show good potential at a demonstration level. In addition, recent studies have indicated that diesel fuels produced from natural gas are significantly less polluting than petroleum derived diesel. Economical conversion of gas streams to liquid products such as fuels and commodity chemicals will allow full use of domestic natural gas supplies while addressing the issue of GHGs.

System Concepts

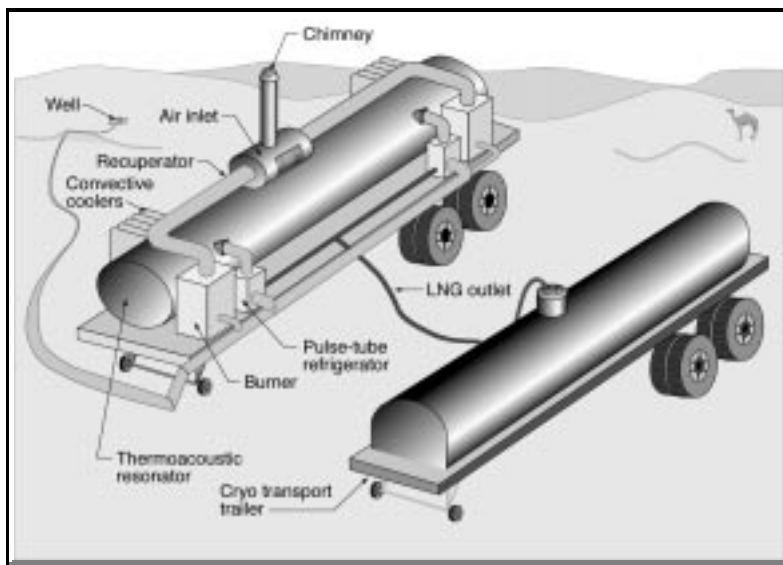
- LNG production: Thermoacoustic natural gas liquefaction produces LNG at lower costs than conventional technology.
- Natural gas diesel fuels: Diesel fuel derived from natural gas far exceeds conventional diesel fuels in reducing emissions including hydrocarbons, carbon oxides, NO_x, and particulates.

Representative Technologies

- Diesel fuels produced via Fischer-Tropsch conversion of synthesis gas have shown low emissions and good efficiency in engine tests.
- In the case of LNG production, process uses direct gas burning to generate sound waves to drive an orifice pulse tube refrigerator. Does not require the use of electricity.

Technology Status/Applications

- Production of LNG from natural gas employing thermoacoustics has been demonstrated at 100 gal/day.
- Diesel fuels produced via conventional synthesis gas technology presently have low yields.



Natural gas liquifier

Current Research, Development, and Demonstration

RD&D Goals

By 2000:

- Demonstrate 500 gal/day production of LNG from natural gas using thermoacoustic processes.
- Identify new catalyst compositions to effectively promote natural gas diesel fuel production.

By 2004:

- Scale up technologies to commercial levels.
- Demonstrate natural gas diesel fuel production at a commercial size.
- Optimize an integrated process using ion transport membranes for conversion of natural gas to synthesis gas, followed by synthesis gas conversion to transportation fuels, and demonstrate natural gas diesel fuel production at a commercial size.

By 2011:

- Produce 200,000–500,000 bbl/day of diesel fuel from remote natural gas sources.

RD&D Challenges

- Research and technology for process improvements are needed to
 - improve modeling of the complex fluid dynamics and nonequilibrium chemistry of the processes to improve process control and process optimization for a variety of input natural gas compositions
 - develop relevant process sensors for automated process control and optimization
 - provide scale design for commercial implementation
- Catalyst development: Identifying catalytic materials that selectively promote high-cetane paraffin formation from synthesis gas is a key for producing diesel fuel from natural gas.

RD&D Activities

- DOE is actively promoting and funding materials, catalyst, and process development for the direct and indirect conversion of methane.
- Industry has targeted natural gas conversion, to both liquid fuels and LNG, as a major research area.
- Significant government/industry research efforts are under way to more effectively convert natural gas to synthesis gas.

Recent Success

- Research over the past 10 years has shown significant improvements in all areas of methane conversion.
- Recent reports indicate that improved yields of high-quality diesel fuels from natural gas can be obtained.

Commercialization and Deployment

- Examples of commercial GTL processes include Mobil's process of converting synthesis gas to methanol followed by conversion to gasoline (1985), Sasol's slurry phase distillate (Fischer-Tropsch) process (1992), Shell's middle distillate synthesis process (1993). Recently, Sasol signed a memorandum of understanding with Qatar General Petroleum Corp. and Phillips Petroleum to build a 20,000 bbl/day plant (Fischer-Tropsch) in Qatar.
- A team headed by Air Products was selected by DOE to head an \$84M research program to develop membrane technology for synthesis gas production.

Potential Benefits and Costs

Carbon Reductions

- GTL provides an effective way to use methane, a GHG.
- Estimates have placed the GHG reduction potential of eliminated leaks at 12 MtC/year in the United States and approximately 300 MtC/year if applied to stop leaks from pipelines in Russia.
- Carbon reduction estimates are 2–4 MtC in 2010, 5–10 MtC in 2020, and 10–15 MtC in 2030.

RD&D Expenditures

- Current DOE RD&D funding for this pathway is approximately \$5M/year.
- Required federal funding: 1.5 times the current level, or \$8M/year through 2030.

Market

- About 2,000–5,000 Mcf per day of natural gas is used to produce 200,000–500,000 bbl/day of high-quality diesel fuel.
- Approximately 80,000 new jobs are created for each 1 million bbl/day of diesel fuel.
- Existing liquid pipeline infrastructure can be used for transportation and distribution.
- Spinoff for LNG includes use by gas utilities for peak demand spikes and natural gas vehicle gas stations.

Nonenergy Benefits and Costs

- Costs: Thermoacoustic LNG production—additional \$500K/year, 5 years, total = \$2.5M; diesel fuel production (catalyst development)—additional \$1M/year, 6 years, total = \$6M; fuel testing in pilot-scale facility, emission impact analysis and optimization, additional \$1M/year, 8 years = \$8M.
- Both natural gas to fuels and LNG will reduce dependence on imported oil.

Risk Factors

Technical Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Technologies have been demonstrated at small scale; however, the challenge of scale-design cannot be minimized.

Commercial Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Liquid hydrocarbon fuels have existing markets, facilities, and infrastructure for transportation and utilization; however, high capital cost facilities may be required.

Ecological Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- Technologies for construction and operation of oil and gas facilities are well developed. Fuels produced by these processes are clean burning with very low sulfur and nitrogen compound emissions.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- Most of the technology for producing and handling natural gas and liquid hydrocarbon products is available, is well understood, and presents no major new risks.

Economic Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- None currently identified.

Regulatory Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

Key Federal Actions

- Collaborative industry/government research efforts could be developed to identify catalysts and processes to economically convert natural gas to liquid diesel fuels.
- More federal funding is needed to begin to address the broad range of technical issues related to commercial scale up, remote construction, and operations.
- A federal mandate to reduce emissions through fuel switches would accelerate this pathway.
- Significant U.S. and international activity is expected in both the GTL and LNG areas through the year 2010 and beyond. There is opportunity for the United States to be the leader in GTL and LNG technologies and market the technology abroad.

5.3 INCREASED NATURAL GAS PRODUCTION

Technology Description

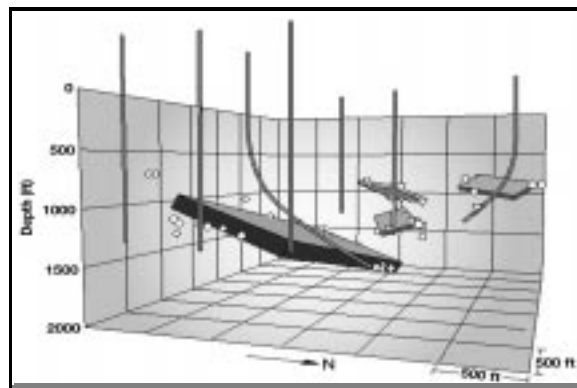
Natural gas as a fuel has a fundamental advantage over oil and coal in terms of reducing carbon emissions because of its lower carbon-to-hydrogen ratio. The United States has an abundant natural gas supply and needs only the development of technology to make it available to displace oil and coal from the power generation and transportation markets. This can be accomplished in the near term through secondary gas recovery (230 Tcf); in the mid-term through low-permeability formation development (500 Tcf), offshore (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 small success rate would be needed to effectively meet the expected demand of 28 Tcf in 2010.

System Concepts

- Improved knowledge of resources to understand the characteristics of gas-in-place and to quantify what is recoverable.
- Increased production efficiency via drilling, completion, and stimulation.
- Effective deployment of technologies in conventional and unconventional resources.
- Advanced storage concepts in areas of demand to minimize service curtailments.
- Development of technology to recover gas from hydrates and deep gas sources.

Representative Technologies

- Advancements in 3-D seismic could reduce risks by 10% for all exploration wells and by 5% for development wells in 2010 (cumulative reserves of 37 Tcf are possible).
- Advancements in drilling, completion, and stimulation are expected to reduce costs associated with recovery (cumulative reserves of 6 Tcf are possible in 2010).
- New technology in gas storage could eliminate a 5% annual loss (cumulative savings of 5 Tcf in 2010).
- Detecting and preventing leaks from natural gas pipelines using backscatter absorption gas imaging and optical methane detectors can detect and prevent leaks from natural gas pipelines (cumulative savings of 5 Tcf in 2010).



Fracture mapping technology

Technology Status/Applications

- Industry focuses on drilling and fracturing with fluids; this technology is not applicable to low-permeability formations.
- Available seismic technology is helpful in locating productive strata but needs improved resolution to locate natural fracture systems that are the “sweet spots.”
- Interest in gas hydrates and deep gas is evolving with detection and characterization in both onshore and offshore environments; coalbed methane development remains stagnant.

Current Research, Development, and Demonstration

RD&D Goals

- The goal of the gas supply program is to expand the national reserve base.
- Low-permeability formations and marginally economic reservoirs are the targets for half of the future gas supply.
- Production tests in coalbeds are needed to fully develop this resource.
- Gas hydrates and deep gas sources are targets for the long-term supply.

RD&D Challenges

- Developing innovative drilling and subsurface diagnostics to eliminate damage to formations while drilling, to improve recovery efficiency from them, and to reduce costs.
- Developing advanced technologies that increase resolution in naturally fractured formations to reduce risks in locating favorable places to drill.
- Improving diagnostics to detect gas hydrates and deep gas resources.

RD&D Activities

- | | |
|--|------------------|
| • Resource and reserve assessments | FY 1997 (\$3.3M) |
| • Drilling, completion and stimulation | FY 1997 (\$5.4M) |
| • Low permeability formations | FY 1997 (\$4.4M) |
| • Natural gas storage | FY 1997 (\$1.0M) |

Note: In the early 1980s, hydrates, deep gas, and coalbed methane characterization work was conducted, but it ended with the passing of the energy crisis. Data remain archived at FETC.

Recent Success

- Maps and databases for use in exploration were published and distributed to industry.
- An air hammer was developed with industry to double the drilling rate in horizontal wells.
- A “dry stimulation” process was introduced to industry to avoid formation damage in wells.
- Vast improvements were made in processing complex 3-D data sets.
- Fundamental understanding of hydrates, deep gas, and coalbed methane has been documented.

Commercialization and Deployment

- Advanced stimulations that avoid formation damage are currently being used in select applications; more customers must be exposed to their merits.
- Improved drilling tools and diagnostics have reached a market plateau over the past 5 years and account for the better recovery efficiency to date with fewer wells.
- Only a limited volume (5%) of available coalbed methane is being produced.
- Widespread deployment of technologies is expected by collaborating service companies.

Potential Benefits and Costs

Carbon Reductions

- This pathway would expand production of natural gas, which could be expected to decrease gas prices, making gas more competitive for electricity production.
- Reductions of 150–200 MtC/year would be achieved if 25% of coal-fired power plants were displaced by natural gas–fueled plants in 2030.
- Carbon reduction estimates for this pathway are 10–20 MtC (2010), 75–100 MtC (2020), 100–200 MtC (2030).

RD&D Expenditures

- Current DOE RD&D funding for this pathway is \$14M/year.
- 1.5 times this current level is required to achieve the estimated carbon emission reductions, or \$21M/year through 2030.

Market

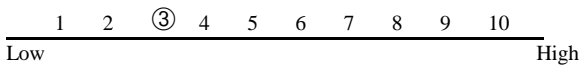
- An assured gas supply could displace 2 million bbl oil /day from switchable stationary markets (25% of *imported oil*).

Nonenergy Benefits and Costs

- Energy security at non-disruptible prices in the market.

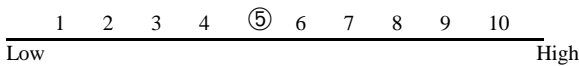
Risk Factors

Technical Risk



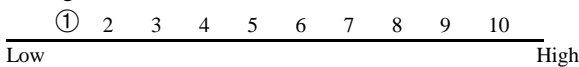
- New technology development is considered a low to medium risk. Widespread acceptance may require demonstrations in every basin for quantification. Support for industry’s offshore production problems may be required.

Commercial Risk



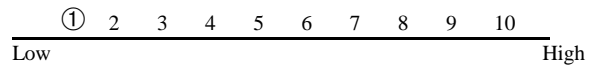
- Drilling and stimulation advances may be hindered by industry’s manner of doing business; if patents are not owned by the vendors, new advances may not find their way into the marketplace.

Ecological Risk



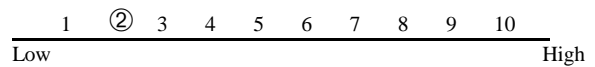
- Not significant.

Human Health Risk



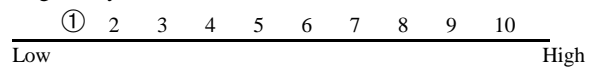
- Not significant.

Economic Risk



- Not likely.

Regulatory Risk



Key Federal Actions

- An optimum funding level (\$300M to 2010 plus \$450M from 2010 to 2030).
- Federal codes to attain emission reductions may be required to influence fuel switching.
- A federal partnership program may be required to instill confidence in new technology.

5.4 CO-PRODUCTION WITH INTEGRATED GASIFICATION COMBINED CYCLE

Technology Description

The IGCC process offers industry low-cost, highly efficient options for meeting market requirements. One of the most efficient and environmentally friendly technologies for producing low-cost electricity, IGCC can process many feedstocks including coal, petroleum coke, biomass, and municipal wastes. In combination with synthesis gas conversion technologies, it is the only technology that can coproduce a variety of commodity and premium products in addition to power to meet future market requirements.

System Concepts

- IGCC for electricity production converts carbonaceous feedstocks in a gasifier into synthesis gas, a mixture of CO₂ and hydrogen. The gas is cleaned of particulates, sulfur, and other contaminants to permit further processing and combusted in a high-efficiency gas turbine/generator. The heat from the turbine exhaust gas is extracted to produce steam to drive a steam turbine/generator.
- In coproduction mode, feedstocks can be processed before gasification to extract valuable components, or the synthesis gas can be converted to products. Valuable precursors from feedstocks such as coal can be extracted to manufacture high-strength, lightweight carbon fibers and anode coke. Clean synthesis gas can be catalytically converted into environmentally superior transportation fuels, high-value chemicals, or hydrogen.

Representative Technologies

- Sasol in South Africa has been converting coal to transportation fuels and chemicals for more than 40 years, but the technologies used are not efficient. Shell has built a plant to convert natural gas to fuels in Malaysia using a combination of new and older technologies. The transportation fuel product is environmentally superior to conventional petroleum products and has commanded a premium price.
- Liquid-phase methanol synthesis is being demonstrated at an Eastman Chemical coal gasification facility. Its design capacity is 80,000 gal/day. The project is demonstrating a new cost-effective route for producing liquid fuels and chemicals in a mode that could be readily integrated with an IGCC plant to coproduce power and fuels/chemicals.

Technology Status/Applications

- IGCC demonstration projects using coal, petroleum coke, or other petroleum refinery wastes are operating or under construction in the United States and worldwide. Many are designed for coproduction to allow improved thermal efficiencies.
- Conversion of synthesis gas to transportation fuels has been investigated for several decades. Significant advances in catalysis and reactor design are generating interest from industry. The environmental superiority of the resulting transportation fuels—which substantially reduce emissions of hydrocarbons, CO₂, and particulates—has been recognized as a key ingredient for meeting future environmental regulations.
- IGCC and IGCC coproduction technologies can be readily integrated into existing refineries and chemical plants to convert waste materials to end products or used to repower inefficient existing plants. The pulp and paper industry produces much biomass waste, most of which is used internally to generate power and steam. Most boilers used in this industry are old and must be replaced, a potential market of 20,000 MW of capacity. Because of the large steam usage in these plants relative to power consumption, IGCC operating in the coproduction mode offers a unique opportunity for steam and power production while simultaneously destroying hazardous chemicals and generating synthesis gas fuel for kiln operation.

Current Research, Development, and Demonstration

RD&D Goals

By 2004:

- Identify low-cost feedstocks (e.g., biomass, municipal waste, black liquor) available in sufficient quantities for commercial applications.
- Evaluate the gasification of low-cost feedstocks in advanced gasifiers either separately or via co-feeding with other carbonaceous materials.
- Reduce consumption of sorbents, catalysts, and filter elements by 40% from today's levels.

By 2006:

- Reduce the cost of IGCC and IGCC coproduction technologies through the use of advanced air separation technologies, advanced gasifiers, high-efficiency gas turbines, and improved synthesis gas cleanup and CO-to-H₂ shift technologies.
- Begin pioneer plant demonstration of IGCC coproduction concept.

By 2010:

- Reduce the installed capital cost of gasifier-based technologies by at least 10% of current designs.
- Demonstrate the reliability, availability, and maintainability of IGCC and coproduction technologies to secure financing of future facilities.

By 2015:

- Demonstrate the modularity for reducing plant cost and demonstrate near-zero discharge of wastes, emissions, and CO₂.

RD&D Challenges

- Reduce the cost of synthesis gas for both power and fuels production.
- Develop catalysts and sorbents that are mechanically strong and have high activity.
- Optimize the design of process facilities to obtain the lowest total installed cost without sacrificing performance and safety.
- Improve materials for high-temperature gas turbines.
- Identify and develop innovative, cost-effective ideas for sequestering or using CO₂.

RD&D Activities

- Develop and demonstrate ceramic membranes for high-efficiency, low-cost oxygen production.
- Optimize the process design and engineering, procurement, and construction activities of IGCC and coproduction facilities.
- Develop advanced gasifier technologies for achieving higher throughput and using a variety of low-cost opportunity fuels such as petroleum coke and biomass.
- Develop and demonstrate advanced, high-efficiency gas cleanup technologies for removing impurities from the gasifier product.
- Develop and demonstrate 2600°F inlet gas turbines, advanced power cycles and fuel cells, and low-temperature catalysts and processes for conversion of synthesis gas.

Recent Success

- Two advanced IGCC Clean Coal demonstration projects have been successfully operated using coal.
- An advanced sorbent for removing sulfur from synthesis gas has been developed with sufficient mechanical strength for use in moving bed and transport reactors. Large scale testing is scheduled.
- Operation of the liquid-phase methanol facility is being demonstrated. The design production rate of 260 tons of methanol per day was achieved on the first day of operation.
- Preliminary diesel engine tests on Fischer-Tropsch fuels from indirect liquefaction show exceptional performance. Combustion efficiency is high and emissions tests show no sulfur oxides, lower NO_x, and significantly lower hydrocarbons than in conventional diesel fuels.

Commercialization and Deployment

- Industry is using slurry reactor and catalyst technology to convert natural gas to methanol, chemicals, and liquid fuels.
- Engine testing done in DOE programs is helping demonstrate the environmental benefits of these advanced fuels.
- Conceptual designs are improving industry's understanding of these processes and reducing the risk of deployment.
- In situ or underground coal gasification can produce high-quality synthesis gas as a feedstock for combined cycle power plants or advanced Fischer-Tropsch processes. The technology has been commercially developed in the former Soviet Union and limited commercial scale testing performed in the United States.

Potential Benefits and Costs

Carbon Reductions

- In the cofeed, coproduction mode, carbon emissions are expected to be a third lower than from separate facilities producing the same amount of power and fuel.
- Transportation fuels produced from synthesis gas contain no sulfur and aromatics and reduce hydrocarbon, CO, and particulates emissions by 25–40% compared with low-sulfur, low-aromatic petroleum diesel.
- If all existing coal-based power plants were replaced with IGCC coproduction technologies, they could produce about 2 million bbl/day of transportation fuels while producing the same power output, but with 15% lower CO₂ emissions (16 MtC/year).
- Coal that is transformed into a liquid using these technologies can sequester excess CO₂ at the point of production. Depending on the type of coal, 30–35% of the carbon from coal could be captured during synthesis gas and liquid fuels production.
- Potential carbon reductions are 245 MtC/year @ 50% efficiency by 2020 and 325 MtC/year @ 60% efficiency by 2030.
- Portions of this potential are estimated in those years: 5–10 MtC in 2010; 50–100 MtC in 2020; and 65–130 MtC in 2030. Carbon reduction estimates are already counted in other pathways (3.3 and 6.1). They should not be added again to these pathways because that would involve double counting.

RD&D Expenditures

- The IGCC program has been funded at about \$50M annually. An annual DOE RD&D budget of \$75M/year through 2030 is required to generate this pathway's estimated carbon reductions.

Market

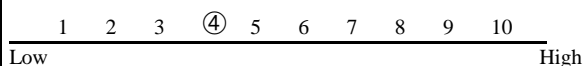
- This energyplex approach presents opportunities to replace a petroleum-based fuel with more abundant coal-based fuels. Currently, 300 GW coal electrical capacity is available in the United States.

Nonenergy Benefits and Costs

- Improve U.S. industrial competitiveness in new technologies.
- Enhance energy security and reduce the trade deficit through use of domestic resources instead of foreign oil.

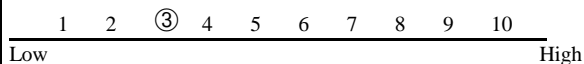
Risk Factors

Technical Risk



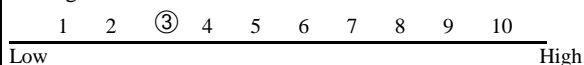
- Advanced materials and technologies for producing them are needed for membranes, catalysts, filters and sorbents.

Commercial Risk



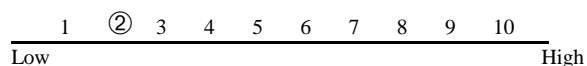
- Operational experience needs to be developed through pilot and demonstration projects.

Ecological Risk



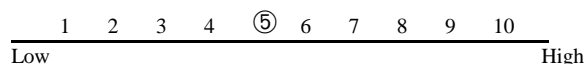
- Fuel testing is needed to demonstrate the performance of these fuels with existing and future engine designs.

Human Health Risk



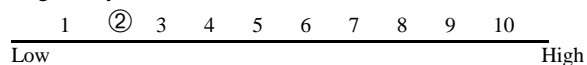
- Life cycle assessments are needed to eliminate or minimize risks.

Economic Risk



- Thermophysical property data and models are needed to improve the accuracy of process designs to reduce financial risks.

Regulatory Risk



Key Federal Actions

- Accelerate the deployment of both IGCC and liquid fuels technologies in the United States.
- Maintain the current level of support in the near term and increase it as the need for advanced demonstration projects materializes.

5.5 CARBON DIOXIDE FOR IMPROVED OIL AND GAS RECOVERY

Technology Description

Each day 50 trillion scf of CO₂ is vented from power plant stack gases in the United States. Also each day, the United States extracts more than 1.1 billion scf of CO₂ from underground deposits and pumps it into oil reservoirs to enhance the recovery of petroleum. Instead, the CO₂ that would otherwise be emitted to the atmosphere (from fossil-fueled combustors) could be captured and used. In the future, CO₂ contained within powerplant stack gases could also be pumped into coal seams to recover methane economically or to replace base gas in storage wells.

System Concepts

- Separate CO₂ from the stack gas of power plants and other combustors and use it in a number of improved oil and gas recovery methods. The CO₂ would have multiple uses for enhanced oil recovery, gas cap maintenance, well stimulation, inert gas replacement in storage, and methane recovery from coalbeds.
- Reject the nitrogen from the air before combustion so that the flue gas is principally CO₂ and water vapor, from which the CO₂ is either separated for food-grade applications or injected as CO₂-rich flue gas to be used in improved oil and gas recovery operations.
- Remove some of the carbon from the fuel (and add hydrogen to fuel) before the fuel is sent to the end user. The removed carbon is available as a concentrated CO₂ stream.
- Capture CO₂ from low-quality natural gas for injection.
- Combine energy recovery and GHG reduction by either capturing the flue gases or removing the CO₂ from stack gases in a setting where a dual fuel (natural gas and coal) power plant is located close to an *in situ* gassy unmineable coalbed. CO₂ from stack gases would be injected into the coalbeds to produce methane, which would be used to fuel or co-fire the power plant. The CO₂ emissions from the plant would then be continuously re-injected into the coalbeds to recover methane.

Representative Technologies

- Passage of flue gas through a solution of monoethanolamine (MEA) (or related compounds).
- The use of an air separation plant in front of an existing power plant.
- Recovery of CO₂ from coal gasification and subsequent use for enhanced energy recovery.
- Upgrade low-quality gas into pipeline methane and use the CO₂ from higher efficiency membrane separation for other applications.
- Co-produce methane and electricity by using CO₂ to produce methane from unmineable coal seams, using the methane to fire a power plant, injecting the CO₂ from the plant's stack gases into the coal seams in a continuing cycle.

Technology Status/Applications

- MEA technology is commercial for applications limited to certain gas streams found at certain chemical plants.
- O₂-CO₂ recycling has been pioneered at the pilot scale in the United States and the results have been duplicated in the United Kingdom, Europe, and Japan. It appears technically suitable for electric power plants but has not been applied because natural CO₂ deposits are less expensive.
- CO₂ recovery from coal gasification produces ~240 million scf per day of CO₂. A project is under way to recover CO₂ at the Great Plains Coal Gasification Plant and pipeline ~100 million scf/per day to the Weyburn oil field in Canada. Additional CO₂ from the pipeline could be used in North Dakota, Montana and Wyoming.
- CO₂ from stack gases or exhaust gases could be used to recover additional enhanced oil and sequester GHGs. There is an increasing industry awareness of the benefits of well stimulation with CO₂ and demand for both low-quality and food-grade CO₂ is expected to gain momentum. The potential use of direct flue gas or exhaust gas needs to be further investigated.
- CO₂ could be used for base gas replacement in gas storage reservoirs. Natural gas itself or nitrogen is currently used, ~4.3 trillion scf.
- Several companies have proprietary data and technology for CO₂ injection into coal for higher yields of methane recovery. Unofficial information from private sources indicates that the process is technically and potentially economically feasible.

Current Research, Development, and Demonstration

RD&D Goals

For the near term, validate the CO₂/CH₄ concepts that will

- Reduce the cost of recovering CO₂ from combustors and lead to a reduction of CO₂ emissions at targeted power plants.
- Demonstrate the stability and permanence of CO₂ storage in coalbeds and gas storage reservoirs and increased production of methane from coalbeds by CO₂ injection.

By 2002, develop and validate the CO₂/CH₄ concepts that will

- Reduce the cost of recovering CO₂ from combustors by 30–50%.
- Demonstrate improved oil recovery from CO₂ well stimulation treatments.
- Demonstrate that methane production from unmineable coalbeds in selected coal power plant regions will permit 10% co-firing, which will further reduce emissions.

By 2005, develop and validate advanced CO₂/CH₄ concepts that will

- Demonstrate the use of stack gas CO₂ as direct flue gas for improved oil recovery.
- Exhibit the performance, reliability, and efficiency to store CO₂ and optimize CH₄ recovery in coals with varying thickness, maturity, and depth.
- Determine the feasibility of directly injecting power plant flue gas to remove stored SO₂ and NO_x as well as CO₂.

RD&D Challenges

- Improve gas-gas separations, particularly the separation of air into oxygen and nitrogen and the separation of CO₂ from nitrogen.
- Conduct research to determine (1) where CO₂ goes upon injection, (2) how it interacts geochemically with the reservoir rock and fluid, and (3) how these interactions affect the recovery of gas and oil.
- Determine influence of water-saturated coalbeds on CO₂ injection and adsorption
- Adapt existing oil and gas well methodologies to CO₂ injection requirements.
- Determine the extent to which the concepts can be applied to the full range of unmineable coals.
- Determine the feasibility of direct flue gas injection.

Current Research, Development, and Demonstration (continued)

RD&D Activities

- RD&D on O₂/CO₂ recycling systems has been carried out (international funding probably equivalent to several million dollars in recent years). DOE funded pioneering work in this area in the mid 1980s; funding was approximately \$2M.
- Analytic and laboratory process studies are ongoing.
- Commercial recovery and use of coalbed methane demonstrated by industry.
- Laboratory and field tests are needed to confirm the fundamental relationships supporting CO₂ injection and methane recovery in a variety of coals and reservoir environments.

Recent Success

- The practice of CO₂ injection has grown significantly. Petroleum production rose from 30,000 bbl/day in 1986 to 171,000 bbl/day in 1996. In 1996, there were 61 CO₂ injection projects in the United States. CO₂ usage associated with well stimulation is increasing as well operators begin to appreciate the benefits, and the service industry begins to capitalize the equipment needed to provide a stimulation service.
- Industry has privately demonstrated the concept of injecting CO₂ into coals for enhanced methane production (proprietary data).
- DOE-sponsored laboratory testing on bituminous coal samples shows the affinity factor of CO₂ to coal surface is 2:1 over CH₄.

Commercialization and Deployment

- A CO₂ pipeline will be constructed in 1999 from the Great Plains Coal Gasification Plant to Canadian oil fields.
- Co-firing and reburn technologies in several U.S. power plants have been demonstrated in joint DOE-GRI-industry partnerships.
- CO₂ is used commercially in enhanced oil recovery, well stimulation, and well remediation applications.
- Industrial R&D on CO₂ displacement of CH₄ in coal seams.

Potential Benefits and Costs

Carbon Reductions

- CO₂ storage capacity in coals and enhanced production of methane from gassy coals is potentially large. Estimates have placed the sequestration potential of this approach at 50 MtC/year. But it is unclear how much of this potential might be realized.

RD&D Expenditures

- Present DOE R&D budget for effort is \$0.
- An annual DOE RD&D budget of \$8–10M/year is required through 2005.

Market

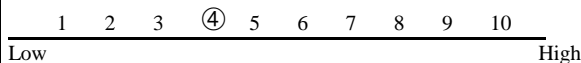
- Increased natural gas production from conventional and tight gas formations with emphasis on coalbeds (coalbed gas now furnishes 5% of U.S. supply at more than 1 Tcf/year and increased reserves and production of domestic petroleum.

Nonenergy Benefits and Costs

- Avoided need and cost for SO_x/NO_x control on power plants whose flue gas is recovered and sequestered in oil wells and coal seams; reduced NO_x and particulate matter through methane use with coal for power; and substantial international market opportunities for the United States.

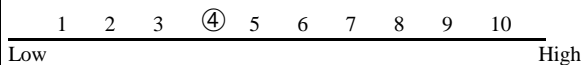
Risk Factors

Technical Risk



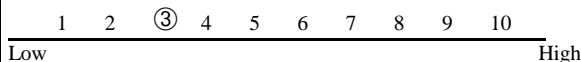
- Improved gas-gas separations are challenging but not infeasible.

Commercial Risk



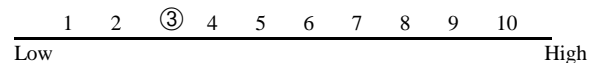
- Little commercial risk after technical risk is removed. Only commercial risk comes from the potential discovery of new unknown deposits of inexpensive CO₂.

Ecological Risk



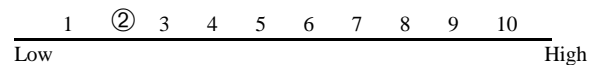
- Properly capped oil fields are known to sequester CO₂. The presence of coal-bed methane suggests that coal beds can sequester gases over geologic time periods.

Human Health Risk

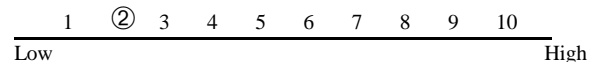


- No increase over present practice.

Economic Risk



Regulatory Risk



- None foreseen.

Key Federal Actions

- Characterization of potential coal resource base geographically with respect to power plant location and regional/local coal properties.
- Economic analysis.
- Pilot demonstrations in United States.
- Government—industry—academia partnerships.

Clean Energy Technologies

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**

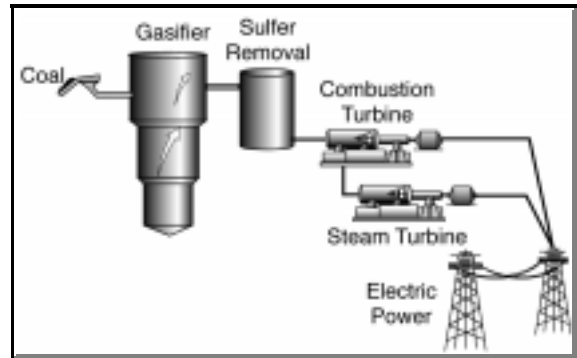
6.1 ACCELERATED DEVELOPMENT OF HIGH-EFFICIENCY COAL-BASED POWER GENERATION TECHNOLOGIES

Technology Description

This pathway will accelerate the development and deployment of high-efficiency coal power generation technologies by 3 to 5 years, reducing CO₂ emissions while maintaining a reliable, low-cost energy supply. Increasing power plant efficiencies ultimately to 55% (compared with current efficiencies of around 33%) will reduce CO₂ emissions by 40% per unit of electricity. With an accelerated RD&D program, deployment can be achieved in the near term, 2000 to 2010. An added benefit is that these plants may be designed to co-fire natural gas or CO₂-neutral biomass fuels with coal and to accommodate other low-cost approaches for CO₂ reduction. Although this pathway assumes no CO₂ sequestration, future development of CO₂ sequestration could reduce carbon emissions to near-zero levels.

System Concepts

- This technology increases power generation cycle efficiency by combining two or more advanced energy conversion cycles.
- System components vary considerably, depending on the specific implementation, but typically include advanced high-temperature, high-pressure cycles and a hot gas expansion cycle, which may be a combustion turbine or an exhaust pressure reduction turbine.
- Steam may also be replaced with a more efficient working fluid (e.g., air, advanced binary mixtures).



Representative Technologies

DOE is currently pursuing:

- Low-emission boiler systems (LEBS).
- Pressurized fluidized bed combustion (PFBC).
- Integrated gasification combined cycle (IGCC).
- High-efficiency power systems (HIPPS) technologies.

Technology Status/Applications

- In DOE plans, LEBS, IGCC, and PFBC technologies with efficiencies of 40–45% are scheduled to be available for commercial deployment by 2000.
- A portfolio of LEBS, IGCC, PFBC, and HIPPS technologies with even higher efficiencies, 50–55%, are scheduled to be available by 2010.
- The cost of electricity for these technologies is expected to be \$0.03 to \$0.04/kWh.
- Costs are expected to decrease as these technologies mature around 2010.

Current Research, Development, and Demonstration

RD&D Goals

- Current DOE RD&D program performance and cost goals range from 42% efficiencies in 2000 to 55%+ efficiencies in 2010 at a cost of electricity of 75–90% of current PC-based generation.
- Emissions of criteria pollutants are targeted to 1/3 to 1/10 of current new source performance standards.
- An accelerated DOE RD&D program would make the higher-efficiency technologies available 3–5 years sooner than the 2010 goal.
- DOE efforts will ensure that these goals are met for the technology portfolio and will foster application.

RD&D Challenges

- Advanced systems need to maintain relatively high temperatures between the combustion/gasification stage and the turbine stage if they are to achieve the efficiency goals.
- High-temperature materials that are stable and resistant to corrosion, erosion, and decrepitation are a primary technology development need.
- Advanced materials are needed 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, CO₂ capture methods, cycle optimization, environmental control technologies with low energy penalties, and solids handling.

RD&D Activities

- The portfolio of high-efficiency coal power systems under development through DOE is LEBS, HIPPS, IGCC, and PFBC.
- DOE support is supplemented by 40% cost share from the private sector.

Recent Success

- In 1996, the IGCC Wabash River project received *Power* magazine's Power Plant of the Year Award, "a technology to bridge the millennium . . . to minimize environmental impact and maximize efficiency."
- As one of 40 projects in the Clean Coal Technology Program, the 260-MW repowering project increased the efficiency of an older pulverized coal unit by one third, to 39% efficiency.

Commercialization and Deployment

- This technology pathway is under development with several recent proof-of-concept greenfield and repowering installations.
- Commercial deployment is scheduled for 2000–2010.
- An accelerated RD&D program could expand deployment and move the deployment time frame up by 3–5 years. Existing plants may be repowered with higher-efficiency coal technologies at or below the price of the natural gas combined cycle (NGCC). Where natural gas is not available (a considerable portion of the United States and a major portion of the international market), high-efficiency coal plants will be the lowest-cost choice.

Commercialization and Deployment (continued)

- The market for new capacity from now until 2010 is estimated to be more than 120 GW in the United States and more than 230 GW internationally. Domestically, the primary competition for this technology pathway is expected to be NGCC.
- Internationally, where natural gas is not available, the market share for coal is expected to be much higher.

Potential Benefits and Costs

Carbon Reductions

- With breakthroughs in CO₂ capture in the next 20 years, systems deployed from this pathway could be retrofitted to achieve near-zero CO₂ emissions. This technology pathway would reduce CO₂ emissions by 40% per unit of electricity in the near term.

2010: 0–10 MtC; 2020: 20–50 MtC; 2030: 65–110 MtC.

RD&D Expenditures

- Funding for the planned DOE RD&D program (excluding the AR&TD program) is projected to be \$780M between 1998 and 2010, or an average of \$60M/year (which was also the annual funding level for FYs 1996 and 1997). An additional 40% in funding will come from private-sector cost sharing.
- Significant increases in funding in the near term would help minimize the technical risk and could accelerate the schedule to commercialization by 3 to 5 years.
- To accelerate this program, it is necessary to move up the commercialization schedule at least 5 years, that is, to provide \$780M between 1998 and 2005. This would increase annual funding to \$98M/year; however, the total funding of \$780M would not increase.

Market

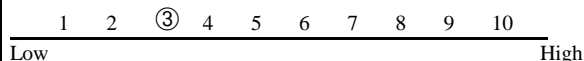
- The major energy impact is to reduce the amount of coal needed per unit electricity, thereby reducing CO₂ emissions.

Nonenergy Benefits and Costs

- International implementation of this technology pathway instead of current low-efficiency technologies will result in major carbon reductions globally. Because much of the international power plant base will be installed in the near future, before 2010, there is a near-term critical window of opportunity to capture international market share and ensure that the highest-efficiency technologies are installed. An accelerated R&D program will enable the United States to capture this larger share of the \$14 trillion export market for energy technologies between now and 2010. Fossil fuel-fired technologies are estimated to represent more than 70% of this market. This technology pathway will create an energy technology export business.

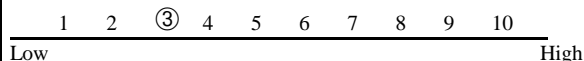
Risk Factors

Technical Risk



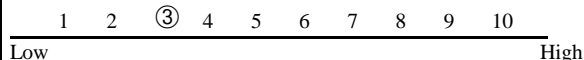
- Most of the risk is in the areas described in RD&D Challenges.

Commercial Risk



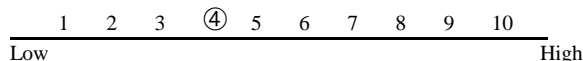
- With the expected increase in demand for electricity and more stringent emissions regulations, a large market demand is expected. Coal resources are virtually unlimited, and no infrastructure changes are required.

Ecological Risk



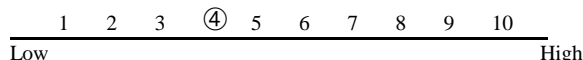
- The ecological risks associated with coal power generation are well known (e.g., coal mining, thermal pollution) and are considered low; this pathway may reduce the risk through higher efficiencies and reduction of criteria pollutants, some of which are acid rain precursors.

Human Health Risk



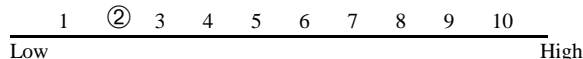
- Air quality will be improved through reduced emissions of SO_x, NO_x, and particulates.

Economic Risk



- Some risk from foreign competition in international markets.

Regulatory Risk



- Advanced technologies under development will surpass compliance requirements for all pollutants.

Key Federal Actions

- Accelerate the DOE RD&D program.
- Provide federal international diplomatic support for penetration of U.S. technologies in the expanding international energy market.
- Provide incentives for early retirement of existing low-efficiency plants in the United States and their replacement or repowering with high-efficiency technologies.

6.2 LOW-CARBON FUELS AND HIGH-EFFICIENCY POWER GENERATION

Technology Description

The ultimate goal for this pathway is to develop systems that use low-carbon gaseous or liquid fuels for highly efficient power generation. These fuels could be natural gas, synthesis gas, hydrogen, or high-hydrogen-content liquids. System components may include fuel cells and ATSSs. This pathway also includes stand-alone applications of small to medium ATSSs, including cogeneration. Near zero CO₂ emissions could be achieved with integration of CO₂ capture.

System Concepts

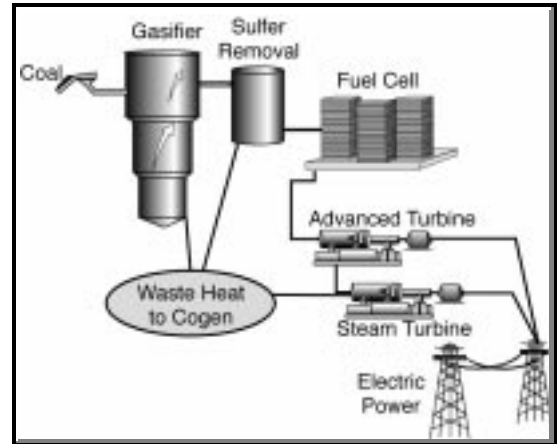
- High-performance power-generating fuel cells.
- High-performance turbines for alternative fuels (such as hydrogen), ultra-high-temperature turbines, and smaller stand-alone turbines for distributed power and cogeneration applications.
- Integrated fuel cells and ATSSs.
- Adaptation of gasification systems covered in the IGCC pathway to the concepts described here, providing a bridge to the hydrogen economy by using coal, through gasification, as a source of hydrogen.
- Designing systems to accommodate natural gas and other fuels such as hydrogen and liquid fuels.
- Integrating CO₂ capture technologies as they become available.

Representative Technologies

- ATSSs
- High-temperature fuel cells
- Methane conversion
- Coal gasification, CO₂ capture

Technology Status/Applications

- ATSSs (hydrogen and ultra-high-temperature), high-temperature fuel cells, and CO₂ capture technologies are under development but not available commercially.
- For coal-based technology, various entrained bed gasification systems are available, and the transport gasifier technology is now being developed by DOE.
- Opportunities still exist to improve gasifier performance significantly for this application.
- Various elements of high-performance cycles that integrate CO₂ capture and other environmental controls need extensive development.
- ATSSs and fuel cells are expected to be used in industrial applications for both power and heat.



Current Research, Development, and Demonstration

RD&D Goals

- For the ATSS program, achieving busbar energy costs that are 10% less than costs of current technology.
- Developing the ATSS and gasification-adaptation technology by 2010.
- By 2010, demonstrating integrated fuel cell and turbine systems achieving efficiencies of 70% on natural gas.
- Also by 2010, lowering fuel cell power system costs to \$1000/kW.
- Demonstrating a hydrogen-fired turbine after 2020.

RD&D Challenges

- Advanced materials.
- Hydrogen transportation and storage.
- Advanced hydrogen separation.
- System-specific energy-efficient environmental controls for NO_x, SO_x, and particulates.
- Developing new components required by advanced cycles integrating CO₂ capture.

RD&D Activities

- Programs for development of
 - Solid oxide fuel cell systems
 - Advanced gas turbine systems
 - Adapting gasification systems from the IGCC pathway
 - Hot gas cleanup
 - System-specific energy-efficient environmental controls
- The FY 1996 and FY 1997 budgets for fuel cells are about \$30M each. The FY 1996 and FY 1997 budgets for ATSSs are about \$40M/year.

Recent Success

- Westinghouse Electric Corporation has a 25-kW solid oxide fuel cell system that has operated successfully for over 13,000 hours.
- The ATSS program has fostered the development of the Westinghouse 501G turbine, which incorporates features developed under this program.

Commercialization and Deployment

- Tremendous potential exists for deployment of ATSS because of the low cost of natural gas.
- Fuel cells are becoming viable in niche applications, and increased production rates for fuel cells are expected to lower capital costs.
- More than 120 fuel cell units (mostly 200-kW size) are operating worldwide.
- Some elements of the more advanced technologies need substantial development before commercialization in the 2010–2020 time frame.
- Some reduction in system costs over time is expected.

Potential Benefits and Costs

Carbon Reductions

- The integrated gasification/fuel cell/ATS will have an efficiency of about 65% and low emissions of CO₂ and criteria pollutants.
- If a hybrid gas turbine/fuel cell system can achieve 70% efficiency and is fueled by natural gas, it produces about 0.069 tonnes/MWh of carbon.
- If fueled by coal at the same efficiency, it produces about 0.123 tonnes/MWh of carbon.
- Other advanced cycles described here will have near zero CO₂ emissions, pending development of cost-effective CO₂ capture technologies.

Until 2010: 0–10 MtC; 2020: 20–30 MtC; 2030: 25–35 MtC.

RD&D Expenditures

- Current plans call for \$436M for fuel cells through 2010 and about \$300M for ATS in the same time period. A substantial increase in investment is required for low-carbon fuels, coal-based technology, and CO₂ capture technology—both near-term and long-term. The annual federal RD&D budget required for this pathway is estimated to be \$160M throughout the three decades.
- Significant industry cost sharing.

Market

- Large domestic and international markets, greater than 200 GW both domestically and internationally.

Energy

- Reduces the natural gas consumption per unit of energy through efficiency improvement.
- Addition of coal gasification as a source of fuel gas will have a positive impact on U.S. energy independence.
- The projected cost of electricity will be 3.5¢ per kWh without CO₂ control.

Nonenergy Benefits and Costs

- Enhances the market for gas turbines and fuel cells and sustains the market for coal-based power system.
- Creates a portfolio of exportable technologies.

Risk Factors

Technical Risk

1 2 3 4 ⑤ 6 7 8 9 10
 Low High

- Some aspects possess development risks; other components are commercial.
- Advanced gas turbine system and solid oxide fuel cells have the lowest risk; hydrogen transport and storage, CO₂ capture, and CO₂ sequestration have the highest.

Commercial Risk

1 ② 3 4 5 6 7 8 9 10
 Low High

- Infrastructure to expand use of gas is largely in place.
- Large domestic resource base, unlimited if methane hydrates can be used.

Ecological Risk

1 ② 3 4 5 6 7 8 9 10
 Low High

Human Health Risk

① 2 3 4 5 6 7 8 9 10
 Low High

- Reduced emissions of criteria pollutants.
- Risks higher for hydrogen.

Economic Risk

1 2 ③ 4 5 6 7 8 9 10
 Low High

- Public would be supportive of implementation.

Regulatory Risk

1 ② 3 4 5 6 7 8 9 10
 Low High

- Commercialization would follow well-established procedures.
- Should not be significantly impacted by deregulation if gas remains plentiful.

Key Federal Actions

- Increase federal funding for RD&D.
- Government/industry/academia partnerships to facilitate technology transfer.
- Risk-sharing program for pioneer plants.

6.3 ULTRA-HIGH EFFICIENCY, ZERO-CARBON EMISSION ENERGYPLEXES

Technology Description

This pathway aims to take advantage of synergies between energy generation, fuels production, and chemical production by integrating these into a single entity, an “energyplex.” Unlike the other pathways in this category, which focus on electricity generation, this one would optimize the entire cycle of carbon utilization by incorporating co-processing concepts, the integral capture of CO₂, and leading to incorporation of carbon into useful products or sequestration. It borrows tenets of industrial ecology where the “waste” materials of one process become raw materials for another. This pathway challenges the R&D community to make significant technology breakthroughs such as novel industrial process configurations, novel power cycles, and coproduction of heat and power.

System Concepts

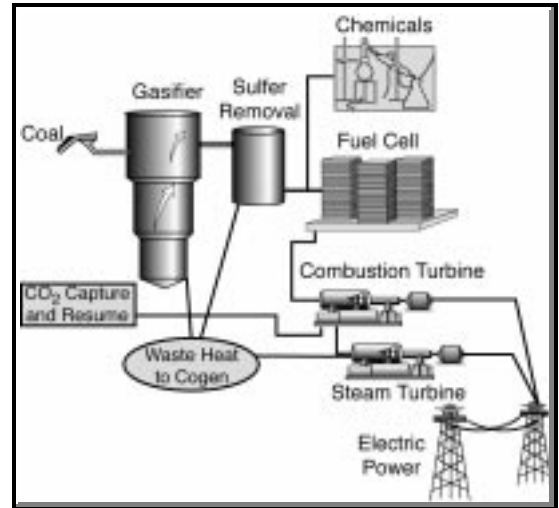
- Focus on supplying distributed power and producing high-value products.
- Flexible system design would allow shifting the product slate (from power to fuels to chemicals or any combination) to optimize income while maintaining environmental performance.
- Modularity would allow construction of plants that are adapted to siting requirements and local resource availability.

Representative Technologies

- Fuel cell/gas turbine bottoming combination to achieve efficiencies of over 70% with integral capture of CO₂. Fuel cell exhaust gases are mixed and burned before expansion through the gas turbine.
- IGCC plants or coal liquefaction plants in combination with existing petroleum refineries using coal.
- Power systems with alternate working fluids.
- Three-phase slurry reactors used in integrated fuel, chemical, and power production.
- High-temperature hydrogen separation membranes and advanced oxygen production techniques.
- Extensions of technologies from the other pathways in this category.

Technology Status/Applications

- Aspects of industrial ecology are already being explored in Europe.
- Solid oxide fuel cell has demonstrated long term performance of over 13,000 hours on a 25-kW stack. Combining a fuel cell and a gas turbine with integral CO₂ capture is still in the conceptualization stage.
- Coal liquefaction is currently in the proof-of-concept stage. Integration with an existing petroleum refinery is still in the concept development stage.



Current Research, Development, and Demonstration

RD&D Goals

By 2015, develop a portfolio of breakthrough technologies (e.g., advanced CO₂ management schemes, advanced hybrid processes and cycles) that would be further developed into energyplexes that will achieve 65% or greater efficiency with COE less than \$0.04/kW and will capture CO₂ safely for reuse. Example subsystem goals are:

- By 2015, develop and verify coal liquefaction technologies that are competitive with crude oil while emitting 20% less CO₂ than current petroleum technologies.
- By 2015, lower energy consumption by 30–40% for oxygen separation via membrane separation.
- By 2015, develop high temperature heat exchanger capable of operating at 2700 °F and 600 psig.
- By 2020, develop and validate combination of fuel cells and advanced gas turbines to achieve efficiencies over 70%.
- By 2030, validate fuel cell systems incorporating carbon capturing methods that achieve near zero CO₂ emissions to the environment, while producing a CO₂ stream.

RD&D Challenges

- Develop process concepts for power plants resulting in zero CO₂ release to the atmosphere.
- Produce hybrid coal and refinery plants to produce fuels, electricity, and chemicals with less CO₂ emitted.
- Produce coal derived fuels at lower costs with less energy usage.
- Simplify manufacturing process and materials in fuel cells to lower costs. Broaden the range of applicable fuel cell technologies.
- Integrate power production with fuels and chemicals.

RD&D Activities

- Membrane research for cheaper separation of oxygen from air and hydrogen from synthesis gas.
- Initiate R&D into fuel cell/gas turbine systems.
- Systems studies are under way to identify novel means of integrating power and industrial processes.
- Work under Technology Pathways 6.1 and 6.2 will form the basis for the R&D to be started in this pathway.

Recent Success

- Liquid-phase methanol technology is being commercially demonstrated at Eastman Chemicals.

Commercialization and Deployment

- This is a long-term futuristic concept and, although certain components are being developed, it is too early to predict the approach to commercialization.
- Westinghouse Electric is the only U.S. solid oxide fuel cell developer.
- Many U.S. developers of gasification technology, including Texaco and Destec.
- First generation likely to impose energy penalty to achieve zero carbon. Energy penalty and cost expected to decline with system refinements.

Potential Benefits and Costs

Carbon Reductions

- An energyplex system including sequestration will have near zero carbon emissions.

2010: 0; 2020: 0–10 MtC; 2030: 20–40 MtC

One process that has been examined would result in attribution of 1/3 of all savings to better thermal integration and the other 2/3 to a particular decarbonization approach. Other concepts could be developed by 2020 which would distribute carbon savings differently between thermal integration and carbon reuse.

RD&D Expenditures

- The R&D budget for fuel cells is about \$30M/year in FY 1996 and FY 1997. The AR&TD budget for power systems is about \$17M/year in FY 1996 and FY 1997.
- Substantial federal funds needed to complete R&D and foster demonstration.
- Current plans call for \$450M for all coal AR&TD through 2010. The accelerated budget would add about \$1250M for this work over the 2100–2030 time frame.
- The annual federal RD&D budget required for this pathway is estimated to be 2000–2020, \$60M/year; 2020–2030, \$50M/year

Market

- Domestic and international markets could be 100s of GWs once commercial.

Energy Impacts

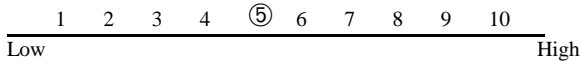
- Reduce the amount of CO₂ produced per MWh of electricity generated.
- Displace imported petroleum with coal derived liquid fuels.

Nonenergy Benefits and Costs

- Helps maintain U.S. technological edge in significant technologies.
- Enhances national security by displacing foreign oil with coal-derived liquid fuels.

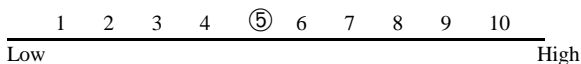
Risk Factors

Technical Risk



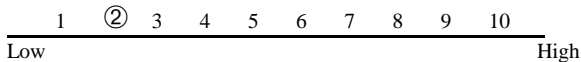
- Moderate technical risk for energyplexes due to integration challenges and needed cost reductions for carbon capture.

Commercial Risk



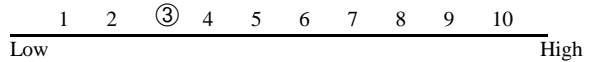
- Requires some infrastructure changes to create energyplex sites.
- Relies on widely available, plentiful domestic fuel resource and technologies.

Ecological Risk



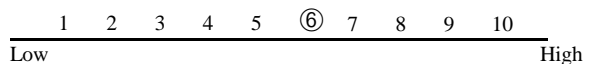
- These coal-based systems face low ecological risks due to near zero emissions.

Human Health Risk



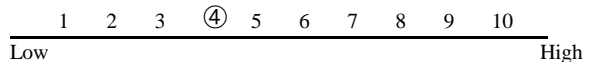
- These coal-based systems face low health risks due to near zero emissions.

Economic Risk



- Public would support extra-low emissions approach.

Regulatory Risk



- Regulatory risk for coal systems is moderate, due to CO₂ and HAPs concerns.

Key Federal Actions

- Federal R&D funding addresses technical barriers and accelerates development of technologies that are still in the conceptual stage of development.
- Encourage energy/industrial/chemical alliances among firms to permit energyplex formation.

Clean Energy Technologies

7. Nuclear

7.1 Lifetime Extension and Generation Optimization

7.2 Next-generation Fission Reactors

7.3 Fusion Power

7.1 LIFETIME EXTENSION AND GENERATION OPTIMIZATION

Technology Description

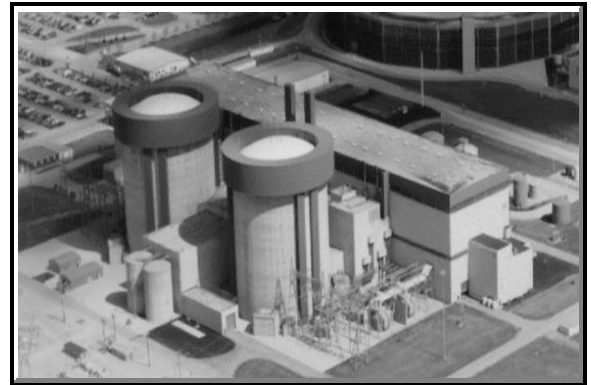
Currently, 107 privately-owned nuclear power plants generate nearly 21% of U.S. electricity (about 100 GWe installed capacity). Nuclear power plants emit negligible GHGs during operation. Technology can be applied to nuclear and nonnuclear equipment in existing plants to enable them to produce more electricity during their operating lifetimes (generation optimization.). The operating lifetimes of existing plants also can be extended safely. Most nuclear power plant licenses will expire between 2005 and 2030. If these plants are shut down and replaced with fossil-based generation, CO₂ emissions will *increase* by >100 million MtC/year by 2030 (at 160 g C/kW- h). Extending the lifetimes and optimizing the generation of these plants for 20 years will avoid 1.4 billion MtC.

System Concepts

- Improve availability and maintainability of nuclear plants.
- Provide technology to predict and measure the extent of materials damage from plant aging and to repair or replace damaged components.
- Operate plants at higher power levels based on more accurate measurement and knowledge of safety margins and reduced consumption of on-site electrical power.
- Develop high-burnup fuel for longer fuel cycles and up to 5% higher energy output.

Representative Technologies

- In situ component and vessel annealing, prediction and monitoring of stress corrosion cracking of reactor internals and steam generators, materials cladding processes
- Advanced technologies for on-line condition monitoring of cables and conventional equipment (pumps, motors, valves, etc.) to minimize production losses from unplanned outages
- Replacing aging, hard-to-maintain safety system electronic components with easy-to-maintain advanced electronics
- Materials measurement and diagnostic technologies to determine the condition and fitness of aged materials
- Cost-effective materials and systems repair technologies
- Advanced core loading strategies; nuclear fuel and cladding research



Technology Status/Applications

- Current technology does not adequately determine residual life; overly conservative margins may result in premature shutdown or refurbishment.
- Replacing major components (e.g., steam generators) may be prohibitively expensive; better techniques are needed.
- Some in-service valve testing technology is in place, but current technology fails to detect a significant number of failures.
- Condition monitoring technology has been developed in DOE/EE Motor Challenge Program and for DOE/DP. Advanced electronics technologies have been developed for high energy physics programs. Development is required for application to nuclear plants.

Current Research, Development, and Demonstration

RD&D Goals

- By 2001, provide technologies that can improve the average capacity factor of nuclear power plants to 86%.
- By 2003, provide technologies to measure, diagnose, and repair effects of aging on plant materials, components, and systems, and develop and demonstrate technologies to reduce the regulatory uncertainties of life extension of plants.

RD&D Challenges

- Successful introduction of technologies that are cost-effective and acceptable to regulators
- Reliable operation of sensors in harsh environments

RD&D Activities

- A previous CRADA between DOE/NE and EPRI started development of advanced electronics to replace Westinghouse safety system components.
- Condition monitoring R&D supported by DOE/NE, DOE/EE, DOE/DP, and NRC is providing a relevant technology base.
- There is no current DOE funding for application of advanced technologies to existing LWRs or for aging research.
- NRC sponsors about \$16M of research related to materials aging.

Recent Success

- Initial industry decision to commercialize DOE electronics technology for replacing Westinghouse safety system components.
- Nonintrusive evaluation of PWR accumulator discharge check valves has reduced testing time and improved reliability.
- Demonstration of gas-fired thermal annealing of Marble Hill reactor pressure vessel completed in 1996.
- Use of hydrogen water chemistry in BWRs to control stress corrosion cracking.

Commercialization and Deployment

- Advanced diagnostic techniques are gaining wider acceptance for evaluating the status of safety-related equipment.
- Successful technology may not be sufficient to extend the life of all plants if adverse regulatory or economic factors dominate.
- DOE/EPRI Sustainable Electric Partnership Agreement provides a basis for DOE/industry cooperation and ensures commercial deployment.
- Technology to support plant license renewal needs to be available in the next 5 years to support initial license renewal submittals to NRC.

Potential Benefits and Costs

Carbon Reductions

- 20-year life extension and generation optimization of part or all of existing 100 GWe installed nuclear capacity reduces carbon emissions by

2010	2020	2030
0–15 MtC/year	20–60 MtC/year	60–110 MtC/year
- Carbon emission avoidance from 1996 to 2030 could exceed 1400 MtC

RD&D Expenditures

- Annual federal RD&D budget required for this pathway: to 2010, \$30M to \$40M/year; beyond 2010, no additional RD&D funds required.

Market

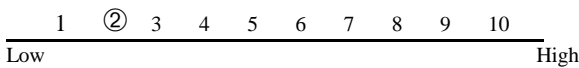
- Indeterminant at this time. Improved operations and life extension could improve the economics of existing nuclear power plants and thus enhance their market acceptance.

Nonenergy Benefits and Costs

- Improves reactor safety because of improved component reliability and better information on component conditions.
- Reduces worker exposures to radiation as a result of shorter maintenance durations.
- Improved U.S. energy security and retention of U.S. nuclear infrastructure, international nuclear influence, and U.S. export potential.

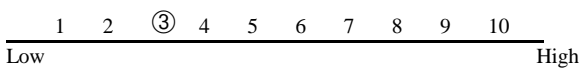
Risk Factors

Technical Risk



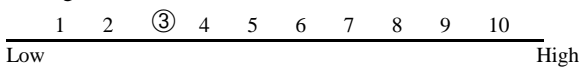
- Technologies require engineering development.

Commercial Risk



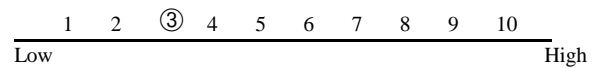
- Technologies must provide cost incentives for industry.
- Regulatory acceptance is issue.

Ecological Risk



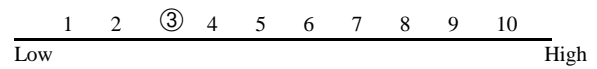
- Reduced wastes and emissions per unit of nuclear energy generated are expected.

Human Health Risk



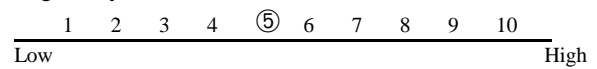
- Reduced worker exposure to radiation per unit of nuclear energy generated is expected.

Economic Risk



- Very high return on investment.

Regulatory Risk



- Required NRC approval and lack of demonstration of nuclear plant license renewal.

Key Federal Actions

- Initiate R&D program for research on existing nuclear plant life extension and generation optimization technologies.
- Continue U.S. support for improved nuclear safety in former Soviet countries to reduce the risk of another major nuclear accident.
- Maintain a healthy U.S. nuclear energy technology and education infrastructure.

7.2 NEXT-GENERATION FISSION REACTORS

Technology Description
<p>A new generation of fission reactors is required to replace or to provide extended capacity for existing LWRs in 2020 and beyond. Evolutionary LWRs of standardized design are available and have received NRC licensing certification. These reactors have been constructed (on schedule) in Japan and South Korea. Advanced LWRs of simplified design and with safety performance based on passive inherent processes are at a late stage of detailed design and NRC review. In the long term, reactors and fuel cycles that are more proliferation-resistant, produce less nuclear waste, and make better use of the energy content in uranium need to be developed.</p> <p>System Concepts</p> <ul style="list-style-type: none"> • Evolutionary and advanced LWR designs: simple, rugged high-design margin, based on proven technologies. Approximately 1300 MWe (evolutionary) and 600 MWe (passively safe), with a design life of 60 years. • Advanced fission reactors and fuel cycles: concepts that aim to extract the full energy potential of the spent fuel from current generation reactors, while reducing or eliminating potential for proliferation of nuclear materials and technologies and limiting the amount of waste produced. <p>Representative Technologies</p> <ul style="list-style-type: none"> • Advanced PWR reactor system 80+ • Advanced BWR • Advanced PWR AP600 • Liquid metal reactors • High-temperature gas-cooled reactors • Thorium cycle nuclear systems • Long-life reactors <p>Technology Status/Applications</p> <ul style="list-style-type: none"> • Several evolutionary fission reactors, including the advanced PWR system 80+ and advanced BWRs, have received NRC design certification and are offered for sale. In addition, the advanced LWR AP600 is expected to receive final design approval and design certification soon. • Advanced reactors and fuel cycles: development is at advanced stage; demonstration is incomplete. — High-temperature gas-cooled reactor development is focused on high conversion efficiency through direct use of the high-temperature gaseous reactor coolant to power a gas turbine driving a generator (i.e., direct conversion). — Advanced fuel cycle development has reached pilot demonstration stage in some cases.
Current Research, Development, and Demonstration
<p>RD&D Goals</p> <ul style="list-style-type: none"> • Advanced LWRs are available for construction. • Future federal research should focus on reactors and fuel cycles that are more proliferation-resistant, produce less nuclear waste, and make better use of the energy content in uranium. <p>RD&D Challenges</p> <ul style="list-style-type: none"> • None for advanced LWRs. • Demonstrate technology for advanced concepts. — Develop proliferation-resistant fuel cycle concepts. — Develop safety, waste, and proliferation aspects of advanced fission reactors. <p>RD&D Activities</p> <ul style="list-style-type: none"> • Federally funded development of advanced reactors and fuel cycles has been terminated in the United States. • Mixed oxide fuel for excess weapons plutonium disposition. • Treatment of selected spent nuclear fuel for waste disposal. • There is no federal RD&D budget for reactor development.
Recent Success
<ul style="list-style-type: none"> • Advanced LWRs have received design certification from NRC. • An advanced BWR is operating in Japan, having been built in less than 5 years.

Commercialization and Deployment

- Advanced LWRs are being developed overseas. Two advanced BWRs are operating in Japan, a system 80+ is under construction in Korea, and two advanced BWRs have been ordered by Taiwan.
- None are foreseen for the United States in the immediate future under present conditions.
- Carbon taxes or other incentives will make advanced LWRs cost competitive.

Potential Benefits and Costs

Carbon Reductions

- Estimated carbon emissions reductions are as follows:

2010	2020	2030
0	~10 MtC/year	10 to 40 MtC/year

RD&D Expenditures

- Little or no funding needed for current generation advanced LWRs.
- Annual federal RD&D budget required for this pathway: to 2010, \$50M/year; 2010 to 2020, \$100M/year; 2020 to 2030, \$150M/year.

Market

- Indeterminant at this time. Potentially large international and domestic markets.

Energy Resources

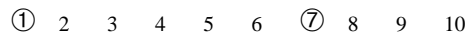
- With full use of the known U.S. uranium resources, nuclear can supply 65,000 quads.

Nonenergy Benefits and Costs

- Energy security; a reduction in dependence on oil.
- Maintenance of U.S. influence in world nuclear arena, facilitating U.S. policy goals.

Risk Factors

Technical Risk



Low High

- For advanced ALWRs, the risk is small.
- Advanced fission reactors require large-scale technology demonstration before commercialization in 2030 and beyond.

Commercial Risk



Low High

- Nuclear power has a mature infrastructure. Lack of purposeful progress toward a waste repository for the spent fuel is an issue. If no plant is ordered, the United States will eventually lose the capability to construct reactors.

Ecological Risk



Low High

- Small.

Human Health Risk



Low High

- Small.

Economic Risk



Low High

- Moderate for advanced ALWRs because of the economic effects of deregulation and political opposition.
- High for other reactors.

Regulatory Risk



Low High

- Low for the advanced ALWRs given NRC design certification.
- Moderate due to required NRC approval and need for demonstration.

Key Federal Actions

- Achieve purposeful progress toward the creation and licensing of a repository for spent nuclear fuel.
- Restart R&D on advanced fission reactor concepts, possibly using international collaboration.

7.3 FUSION POWER

Technology Description
<p>Particle inertia or magnetic fields are used to confine a hot plasma to produce energy from deuterium/tritium fuel. Deuterium is abundantly available from water, and tritium is produced within the fusion plant from abundant lithium. The energy of the fusion reactions is used to generate electricity at central power plants.</p> <p>System Concepts</p> <ul style="list-style-type: none"> • Strong magnetic fields produced by superconducting coils confine plasmas with temperatures of several hundred million degrees Celsius. Some heat from the fusion reactions remains in the fuel to sustain its high temperatures; the rest is carried out by neutrons to be absorbed in a surrounding blanket that serves both as a heat source to produce power and as a medium for producing the tritium. • Compressed fuel microcapsules ignite and burn, producing repetitive pulses of heat in a reaction chamber. Multiple chambers for each beam can improve efficiency, and flowing liquid metal walls in the chamber can serve as blankets. <p>Representative Technologies</p> <ul style="list-style-type: none"> • Large, high-current density superconducting magnets, ion beams (energies 100–1000 keV), millimeter wave high-power microwaves, high-power radio-frequency sources and launchers, and particle fueling apparatus. • Heavy and light ion beam accelerators, solid-state and excimer-gas lasers, and target fabrication technologies are required for inertial fusion. • Structural materials with low activation properties will eventually be required to fulfill the ultimate potential of fusion devices. Tritium generation and heat recovery systems are other common nuclear system technologies required for both. <p>Technology Status/Applications</p> <ul style="list-style-type: none"> • Moderate size fusion experiments in tokamaks, with plasmas at temperatures needed for power plants, have produced more than 10 MW of fusion power. • A commercial power plant scale tokamak (1500 MW_{th}) is being designed in an international project by the world's major fusion institutions. • The physics of sub-ignited targets has been developed with glass lasers, and underground test results have resolved feasibility questions of high gain for power plants. • The target physics of ignition and high gain, using glass lasers, are objectives of the National Ignition Facility (NIF), now under construction.
Current Research, Development, and Demonstration
<p>RD&D Goals</p> <ul style="list-style-type: none"> • Optimize the toroidal magnetic option for an attractive fusion power plant; maintain a vigorous search for improved magnetic concepts; and collaborate in an international project to demonstrate sustained fusion power production at the gigawatt (thermal) level in a tokamak. • Establish the technological basis for an efficient, low-cost ion beam using an induction accelerator, and demonstrate useful gain from compression and burn of NIF targets. • Qualify low-activation materials that allow fusion plants to achieve their ultimate environmental potential. <p>RD&D Challenges</p> <ul style="list-style-type: none"> • Develop magnetic geometries optimal for heat containment that at the same time (1) minimize technical complexity, (2) maximize fusion power density for good economics, and (3) operate in a continuous mode. • Understand target requirements for high gain; reduce the development cost of candidate drivers; and develop long-life chambers and low-cost microcapsule targets. • Develop low-activation materials that also meet structural and compatibility criteria. <p>RD&D Activities</p> <ul style="list-style-type: none"> • Coordinated world-wide magnetic fusion physics efforts center on improved performance. Programs to advance various technologies are proceeding at different paces, with materials and nuclear technologies lagging. • Inertial fusion efforts are concentrated on igniting fusion targets. • Modest efforts to develop beam and laser driver technologies have begun in several programs around the world. • The FY 1997 U.S. budget is \$232M.
Recent Success
<ul style="list-style-type: none"> • More than 10 MW of fusion power was produced in a tokamak for about 1 second, using deuterium-tritium fuel. • New tokamak modes of operation that could lead to high-performance continuous operation have been discovered. • Results from underground tests in the United States have resolved fundamental questions of feasibility of high gain for efficient fusion power plants. • Results from the NOVA laser at Lawrence Livermore National Laboratory have confirmed the validity of computer models used to predict ignition and gain in the NIF. • Vanadium alloys show promise as a low-activation structural material in magnetic fusion devices, and liquid walls for inertial fusion chambers promise to avoid life-limiting radiation damage.

Commercialization and Deployment

- Large central-station electrical generating plants could be commercialized late in the second quarter of the twenty-first century; the timescale depends on a sustained international effort and success in that R&D.
- Fusion power plants would replace aging and environmentally abusive power generators and fill a potential multi-billion dollar market sector.
- Many technologies developed for fusion are currently used in the commercial sector. Prominent are plasma processing for etching semiconductor chips, hardening of metals, thin-film deposition, and plasma spraying and lighting applications. Other applications arising from this research include medical imaging, heat removal technologies, destruction of toxic waste, X-ray lithography and microscopy, micro-impulse radar, precision laser cutting, large-scale production of precision optics, and high-power microwave and accelerator technologies.

Potential Benefits and Costs

Carbon Reductions

- By late in the next century, fusion power could reduce carbon emissions by 500 MtC/year.

RD&D Expenditures

- FY 1997 federal RD&D expenditures were \$232M.
- PCAST has recommended the federal budget increase to \$280M/year. This study agrees with that funding estimate. This level would maintain a program focused on three key principles: (1) a strong domestic core program in plasma science and fusion technology; (2) a collaboratively funded international fusion program focused on ignition and moderately sustained burn; and (3) participation in an international program to develop practical low-activation materials for fusion energy systems.
- Present worldwide levels (~\$1.5B/year) are required through 2020. When large-scale pilot or demonstration plants are appropriate, additional funding may be needed.

Market

- Undetermined at this time.

Energy

- Could provide unlimited energy if economically viable.

Nonenergy Benefits and Costs

- Energy security, owing to the easy availability of its fuel, would be ensured. Fusion plants present no proliferation issues and are inherently safe against thermal runaway excursions.

Risk Factors

Technical Risk

1 2 3 4 5 6 7 ⑧ 9 10

Low High

- The scientific risk is moderate. Confidence in producing fusion power will come from the next (international) step in the magnetic fusion program and the NIF research on targets.
- Technology risk is high, given the technical complexity.

Commercial Risk

1 2 3 4 5 6 7 ⑧ 9 10

Low High

- Marketplace energy cost is 2–3 cents/kWh; power costs are 6–10 cents/kWh. The cost of fusion power could improve somewhat; competing systems may become more costly if environmental costs are included.

Ecological Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- Operation poses very low ecological risk.
- If low-activation materials are used, plant decommissioning generates low-level waste of low risk to the environment.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- Health risks to the public are low, and worker health and safety should be controlled by procedures.

Economic Risk

1 2 3 4 5 6 7 ⑧ 9 10

Low High

- Plant capital costs will be high.

Regulatory Risk

1 2 3 4 5 6 7 8 9 10

Low High

- Not applicable. Fusion should come under regulations different from those for fission.

Key Federal Actions

- Federal R&D funding for fusion is essential and requires a long term commitment.
- The United States' part in the international effort needs to be strongly coordinated with all other work in fusion.
- Industrial involvement will be essential once feasibility is established.

Clean Energy Technologies

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**

8.1 BIOMASS ELECTRIC

Technology Description

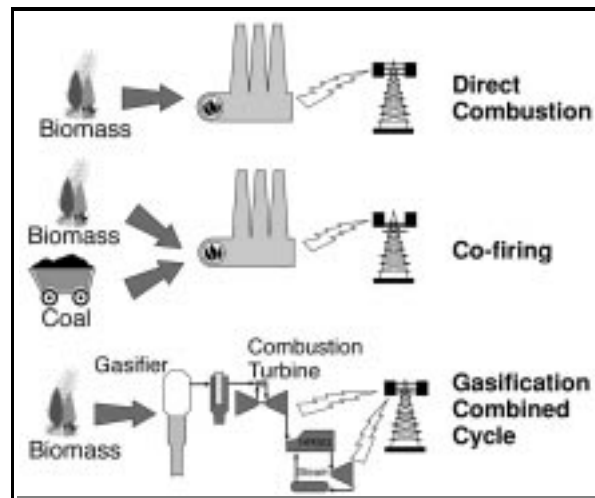
Biomass electric, also called biomass power or biopower, is the generation of electric power from biomass resources ranging from agricultural and forest product residues to crops grown specifically for energy production. Biopower reduces GHG emission by substituting biomass for coal in existing power plants or using biomass alone in plants that displace new fossil plants. Since biomass absorbs CO₂ as it grows, the entire biopower process of growing, burning, and regrowing biomass can result in very low CO₂ emissions, depending on the amount of fossil fuel used for fertilization, cultivation, transportation, and so on.

System Concepts

- Direct combustion systems burn biomass in a boiler to produce steam that is expanded to produce power.
- Cofiring substitutes biomass for coal in existing coal-fired boilers. The highest levels of cofiring (15% on a heat input basis) require separate feed preparation and injection systems.
- Gasification converts biomass to a fuel gas that can be substituted for natural gas in combustion turbines.

Representative Technologies

- For the near term, cofiring is the most cost-effective method. Large coal-fired plants are more efficient (35%) than typically smaller biomass-only plants (20%).
- Biomass gasification combined cycle plants promise comparable or higher efficiencies (> 40%) using only biomass because they are more efficient than steam cycles. Other technologies being developed include integrated gasification/fuel cell concepts.



Technology Status/Applications

- The existing biopower industry, nearly 1000 plants, consists of direct combustion plants with a small amount of cofiring. Plant size averages 20 MWe, and the biomass-to-electricity conversion efficiency is about 20%. Grid-connected electrical capacity has increased from less than 200 MWe in 1978 to over 7500 MWe. More than 70% of this power is cogenerated with process heat in the forest products and sugarcane industries. Wood-fired systems account for 88%, landfill gas 8%, agricultural waste 3%, and anaerobic digestion 1%. In addition, about 2650 MW of municipal solid waste cogeneration capacity exists. Prices range from 8 to 12¢/kWh.
- Biomass gasification for large-scale power production is being commercialized. It will be an important technology for cogeneration in the forest products and sugarcane industries, as well as for new base load capacity. The projected cost of electricity from a gasification plant of 50 MWe or more is ~8¢/kWh.

Current Research, Development, and Demonstration

RD&D Goals

By 2005:

- Develop feedstock crops with a yield potential of 6–8 dry ton/acre/year.
- Reduce the capital cost of gasification-based systems to <\$1900/kW.
- Establish 2000 MW of cofired capacity.

By 2010:

- Reduce the capital cost of gasification-based systems to <\$1500/kW, giving an energy cost of 4–5¢/kWh using energy crops.
- Expand cofired capacity to over 5000 MW.
- Establish approximately 2000 MW of gasification-based capacity.
- Increase the recovery and use of landfill gas significantly at more than 5000 sites.

By 2020:

- Demonstrate advanced gas turbine technologies with biomass gasification.
- Demonstrate biomass–fuel cell power technology
- Reduce the capital cost of gasification-based systems to <\$1200/kW.
- Develop feedstock crops with a yield potential of 8–10 dry ton/acre/year.
- Develop a total biomass-based generating capacity in excess of 30,000 MW.
- Research on advanced concepts such as fuel-cell/thermophotovoltaic hybrids

RD&D Challenges

- Resolving ash chemistry and deposition issues in cofiring applications and establishing cofiring ash as an acceptable material for coal ash markets.
- Determining mechanisms of and the best methods to achieve NO_x reduction in cofiring.
- Demonstrating long-term operation of gas turbines on cleaned biomass synthesis gas.
- Resolving gaps in data required for life-cycle analyses to verify carbon savings (e.g., soil carbon, GHG effects of composting yard waste).
- Resolving materials issues for increasingly severe environments for combustion and gasification/gas turbine systems.
- Fostering successful energy crop business structures.

RD&D Activities

- Complementary activities are under way at several DOE laboratories in cofiring and crop development, along with supporting R&D in USDA. One program has four on-going efforts to establish feedstock provider systems and, in phases, perform detailed plant design, permitting, and eventually technology demonstration for cofiring, direct combustion, and gasification systems.
- DOE Biomass Power Program funding was \$26M in FY 1997.

Recent Success	
<ul style="list-style-type: none"> Identifying the fouling mechanisms in commercial combustion equipment provided a way to mitigate the problem and has resulted in innovative approaches to alternative combustion technologies. One approach is applying ceramic filter elements to the hot-gas cleaning process for high-pressure air gasification; it is currently in long-term testing. 	
Commercialization and Deployment	
<ul style="list-style-type: none"> Biopower capacity in the United States is 10 GW; ~2/3 is grid-connected, and the remaining facilities offset power purchases. Capacity in the rest of the world is about 20–25 GW. U.S. investment in equipment is \$300M to \$500M/year. At least six major engineering procurement and construction companies and several multinational boiler manufacturers are active. Competing technologies include low-cost subsidized fuels abroad and biomass technologies developed in Scandinavia. Guarantees and warranties are a significant issue, giving established technologies an advantage despite their lower efficiency and higher carbon emissions compared with advanced IGCC and other advanced modular technologies. The critical challenge to widespread deployment is cost and reliability of the fuel supply, especially outside industries such as sugar and pulp and paper. Lack of well-demonstrated performance of advanced technologies continues to be a barrier to implementation. 	
Potential Benefits and Costs	
<p>Carbon Reductions</p> <ul style="list-style-type: none"> 2010: 10–20 MtC/year; 2020: 15–25 MtC/year; 2030: 25–40 MtC/year (not including landfill gas). This assumes significant RD&D investment in crop and infrastructure development, optimizing cofiring benefits and costs, and demonstrating gasification-based technologies. It is assumed that cofiring will directly replace coal power generation and gasification systems will replace the average power system carbon emissions. <p>Market</p> <ul style="list-style-type: none"> The estimated cofiring cumulative capacity is 5750 MW in 2010 and beyond, including 400 MW of existing capacity. The estimated direct combustion capacity is about 7000 MW currently, 8250 in 2010, 8650 in 2020, and 9100 in 2030. The estimated IGCC capacity is 1,950 in 2010, 7,100 in 2020, and 16,350 in 2030. <p>Nonenergy Benefits and Costs</p> <ul style="list-style-type: none"> Rural economic development due to employment in feedstock production and transportation. Major export potential (cumulative 3 trillion kWh demand growth in non-OECD Asia through 2010); potential job reductions in mining industry. 	<p>RD&D Expenditures</p> <ul style="list-style-type: none"> DOE Biomass Power Program funding: ~\$24M in FY 1996 and \$26M in FY 1997; no other significant federal funding. U.S. funding including the private sector: ~\$36M. The largest non-U.S. effort is within the European Union. Total public and private investment in R&D is about \$50M. Estimated federal funding required to achieve the target market penetrations is \$69M/year in 2000–2010, \$87M/year in 2010–2020, and \$127M/year in 2020–2030.
Risk Factors	
<p>Technical Risk</p> <p style="text-align: center;">1 2 ③ 4 5 6 7 8 9 10</p> <p>Low High</p> <ul style="list-style-type: none"> Cofiring and direct combustion systems are lower; IGCC with residues and energy crop development are higher. <p>Commercial Risk</p> <p style="text-align: center;">1 2 3 ④ 5 6 7 8 9 10</p> <p>Low High</p> <ul style="list-style-type: none"> Cofiring is lower and feedstock development is higher. <p>Ecological Risk</p> <p style="text-align: center;">1 2 ③ 4 5 6 7 8 9 10</p> <p>Low High</p> <ul style="list-style-type: none"> Conversion system risk is low; dedicated feedstock production depends on other land uses displaced. 	<p>Human Health Risk</p> <p style="text-align: center;">1 ② 3 4 5 6 7 8 9 10</p> <p>Low High</p> <ul style="list-style-type: none"> Risks are mainly from particulate and other emissions from power plants, plus feedstock production and transportation. <p>Economic Risk</p> <p style="text-align: center;">1 2 3 ④ 5 6 7 8 9 10</p> <p>Low High</p> <ul style="list-style-type: none"> Positive employment impact, requires less subsidy than many other renewables, develops technology for export markets. <p>Regulatory Risk</p> <p style="text-align: center;">1 2 ③ 4 5 6 7 8 9 10</p> <p>Low High</p> <ul style="list-style-type: none"> Number reflects the overall risk associated with utility regulation/deregulation, as well as farm policy. Risks comparable to those for other electricity generating technologies.
Key Federal Actions	
<ul style="list-style-type: none"> Continued funding of RD&D in biopower and feedstock areas as outlined Regulatory reforms: DFSS to be classified as agricultural for tax purposes Codes and standards: address standards activities for both biomass feedstock trade and the beneficial use of ash Federal procurement—in the area of modular systems—for its land management and defense arena, plus significant demonstration activities R&D activities in progressively more advanced conversion technologies (e.g., fuel cells and hybrid cycles). 	

8.2 WIND ENERGY

Technology Description

Wind turbine technology converts the kinetic energy in the wind to mechanical energy and ultimately to electricity. Grid-connected wind power reduces GHG emissions by displacing the need for natural gas- and coal-fired generation. Village and off-grid applications are important for displacing diesel generation and for improving quality of life, especially overseas.

System Concepts

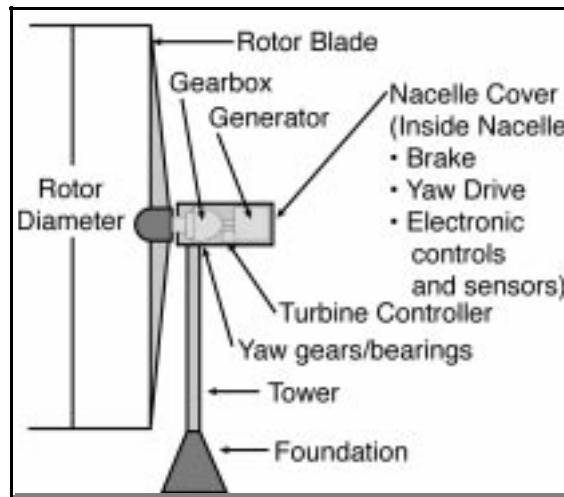
- The principle of wind energy conversion is simple: wind passing over the blade creates lift, producing a torque on the rotor shaft that turns a gearbox. The gearbox is coupled to an electric generator that produces power at the frequency of the host power system.

Representative Technologies

- Two major design approaches are being used: (1) typical of historic European technology—stiff, heavy machines that resist cyclic and extreme loads, and (2) lightweight, flexible machines that bend and absorb loads, primarily being developed by U.S. designers. Several alternative configurations within each approach are being pursued.

Technology Status/Applications

- Thirty-seven states have land area with good winds (13 mph annual average at 10 m height, wind class 4, or better).
- Current performance is characterized by leveled costs of 3 to 7¢/kWh (depending on resource intensity and financing structure), capacity factors of 25 to 35%, availability of 95 to 98%, total installed costs of \$1000/kW, and efficiencies of 65 to 70% of theoretical (Betz limit) maximum.



Current Research, Development, and Demonstration

RD&D Goals

- Windfarm cost/performance varies by wind resource class, ownership type, and time. Current costs are 4 to 7¢/kWh; goals in 2000 are 2.5 to 4.4¢/kWh; goals in 2010 are 2.0 to 3.1¢/kWh; goals in 2030 are 1.7 to 2.8¢/kWh.

RD&D Challenges

- Optimize a wind turbine system to operate for 30 years in a fatigue-driven environment with minimal or no component replacements using knowledge of the wind inflow, operative aerodynamics, resulting structural dynamics, and optimal control of the turbine and windfarm. Understanding the interactions between the wind input and among components as turbine size increases is the fundamental challenge.

RD&D Activities

- Core and university research: wind characteristics, aerodynamics, structural dynamics and fatigue, control systems for turbines and hybrid systems. FY 1998 request: \$14.1M.
- Turbine research: cost-shared design and testing of next-generation utility-grade turbines, improvements in existing turbine designs, verification of performance of turbine prototypes, and development of small turbines using tools and methods from the larger turbine effort. FY 1998 request: \$19.7M.
- Cooperative research and testing: prototype testing at the National Wind Technology Center, collection of wind turbine performance data and related analysis, support of industry stakeholders such as the National Wind Coordinating Committee, and support for international consensus standards and certification for wind turbines as required in overseas markets. FY 1998 request: \$9.1M.
- DOE appropriations were \$32M in FY 1996 and \$29M in FY 1997, and there is no other significant federal funding. The European Union and member countries spend about \$120M per year.

Recent Success

- In 1989 the wind program set a goal of 5¢/kWh by 1995 and 4¢/kWh by 2000. The program and the wind industry met the goals as part of dramatic cost reductions from 25–50¢/kWh in the early 1980s to 3–7¢/kWh today (depending on wind resource and financial structure).
- The National Wind Technology Center (operated by the National Renewable Energy Laboratory in Golden, Colorado), is recognized as a world-class center for wind energy R&D and has many facilities not otherwise available to the domestic industry or its overseas competitors.
- The worldwide annual market growth rate for wind technology is at a historic maximum of 20% with new markets opening in many developing countries. Domestic public interest in environmentally responsible electric generation technology is reflected in the success of “green marketing” of wind power across the country.

Commercialization and Deployment

- Wind technology is competitive today only in high-value niche applications or markets that recognize non-cost attributes. It should be competitive by 2005 without changes in policies and should have no added cost after that. Substantial cost reductions are expected.
- For windfarm or wholesale power applications, the principal competition is natural gas for new construction. Utility restructuring is a critical challenge to increased deployment in the near term because it emphasizes short-term, low-capital-cost alternatives and lacks public policy to support deployment of sustainable technologies like wind energy.
- About 1790 MW of capacity are installed in the United States, principally in California, although projects in Minnesota, Iowa, Vermont, and Texas have recently been installed. Worldwide, 7000 MW is installed and large growth rates illustrate the industry's ability to rapidly increase production with the proper market incentives.
- In the United States, the wind industry is thinly capitalized, except for the acquisition of Zond Corporation by Enron, and there have been two bankruptcy filings recently. About six manufacturers and six to ten developers characterize the U.S. industry.
- In Europe, there are about 12 turbine manufacturers and about 20 to 30 project developers. European manufacturers have established North American manufacturing facilities and are actively seeking sales.
- Initial lower levels of wind deployment (up to 15–20% of the total U.S. electric system capacity) are not expected to introduce significant grid reliability issues. Inasmuch as the wind blows only intermittently, intensive use of this technology at larger penetrations may require additional backup capacity or ancillary services.

Potential Benefits and Costs

Carbon Reductions

- Wind energy produces zero carbon emissions per kilowatt hour.
 - Wind energy without additional storage can reduce GHG emissions through displacing coal- and natural gas-fired power plants.
- 2010: 3–6 MtC/year; 2020: 15–30 MtC/year; 2030: 30–45 MtC/year

RD&D Expenditures

- Federal funding in FY 1997 was \$29M.
- Annual average funding of \$93M is needed 2000–2010; much of this is for hardware testing in 2000–2005. For 2011–2020, about \$28M/year is needed; for 2021–2030, about \$23M/year is needed.

Market

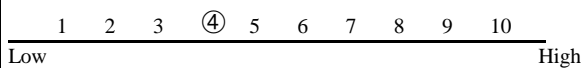
- The principal market for wind energy is substitution for new natural gas combined cycle plants (expected to be 57 GW in 2010 and 348 GW in 2030) and replacement of coal-generated power plants (expected to be 304 GW in 2010 and 424 GW in 2030).

Nonenergy Benefits and Costs

- Benefits include no air emissions through use of wind, low fuel risk, short construction times, modular technology, and sustainable development. For village power systems, benefits include displaced high-cost diesel fuel, carbon offsets, and improved rural quality of life.

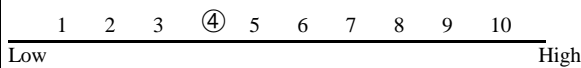
Risk Factors

Technical Risk



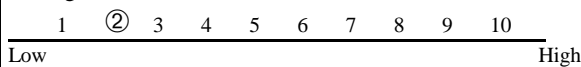
- Risk is mitigated by multiple technical approaches to achieve cost/performance projections.

Commercial Risk



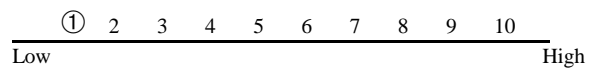
- Near-term , policies are needed that recognize non-cost values such as climate change mitigation and other societal factors. Ultimate impact of green pricing programs is unknown. Infrastructure changes are virtually none in the near term, but significant in the far term. Resource base is unlimited.

Ecological Risk



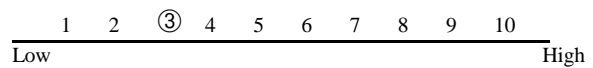
- Minimal because there are no emissions and minor land use impacts. Visual, avian, and noise impacts must be considered for large projects.

Human Health Risk



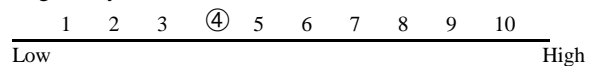
- Properly sited wind energy development should have no impact on human health.

Economic Risk



- Near-term utility restructuring issues increase competitive risk. Public perception is positive.

Regulatory Risk



- Many potential impacts from the outcome of utility restructuring, the need for early deployment incentives, continuation of research funding, tax parities, many levels of government involved.

Key Federal Actions

- Support a strong RD&D program, including power system integration, transmission, and energy storage needed for high penetration.
- Provide near-term market stimulus to overcome barriers, resulting in several competitive manufacturers with domestic and international sales.
- Develop a restructured electric market that recognizes non-cost benefits of wind and the externalities of conventional fossil/nuclear through incentives, pollution taxes, mandates, etc.
- Ensure U.S. technology is competitive in international market (certification, tied aid).

8.3 ADVANCED HYDROPOWER

Technology Description

Advanced hydropower technology improves on available techniques for producing hydroelectricity by eliminating adverse environmental impacts and increasing generation and other operational efficiencies. Current technology often has adverse environmental effects, such as fish entrainment/impingement and the alteration of downstream water quality and quantity. The goal of advanced hydropower technology is to maximize the use of water for hydroelectric generation while eliminating these adverse side effects.

System Concepts

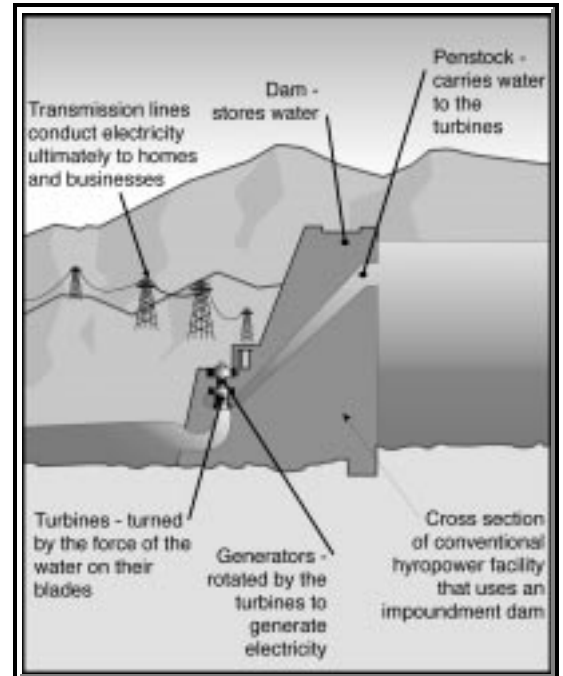
- Conventional hydropower projects use either impulse or reaction turbines to convert kinetic energy in flowing/falling water to turbine torque and power. Source water is either diverted from free-flowing rivers/streams/canals or released from upstream storage reservoirs.
- Improvements and efficiency measures are needed in dam structures, turbines, generators, substations and transmission lines, and environmental mitigation technology to sustain hydropower's role as a clean, renewable energy source.

Representative Technologies

- Autoventing turbines to increase dissolved oxygen in discharges.
- Reregulating and aerating weirs used to stabilize tailwater discharges and improve water quality.
- Adjustable-speed generators producing hydroelectricity over a wider range of heads and providing more uniform instream flow releases without sacrificing generation opportunities.
- Fish-friendly turbine designs that minimize entrainment mortality during passage.
- New assessment models to determine instream flow needs of fish below hydropower projects.
- Advanced instrumentation and control systems that adapt turbine operation to maximize environmental benefits.

Technology Status/Applications

- Hydropower currently generates 10% of the nation's electricity, including 98% of the electricity produced from renewable sources.
- Existing hydropower generation is declining because of a combination of real and perceived environmental problems, regulatory pressures, and changes in energy economics (deregulation, etc.); potential hydropower resources are not being developed for similar reasons.
- Some new, environmentally friendly technologies are being implemented, but lack of financial incentives are hindering rapid development.
- After a successful conceptual design phase, DOE's Advanced Hydropower Turbine System (AHTS) program is stalled as a result of lack of funding.



Current Research, Development, and Demonstration

RD&D Goals

- By 1999: Develop a quantitative understanding of the responses of fish to multiple stresses inside a turbine and produce biological performance criteria for use in advanced turbine design.
- By 2001: Complete environmental mitigation studies on topics such as instream flow needs to produce more efficient and less controversial regulatory compliance.
- By 2005: Complete full-scale prototype testing of AHTS designs, verifying biological performance.

RD&D Challenges

- Develop computational fluid dynamics models of forces inside hydropower turbines that can predict stress levels on fish and can be used in advanced turbine design.
- Demonstrate the cost-effectiveness of retrofitting new technology at existing hydropower plants.
- Quantify the biological response of fish and other organisms so that environmental mitigation can be designed effectively.

RD&D Activities

- DOE funding was \$1M/year in FY 1997, and there is no other significant federal funding.
- DOE's AHTS program has completed Phase I conceptual designs; industry initially provided approximately 50% of the funding for this program but has been unable to continue support because of financial pressures from deregulation.
- Large annual hydropower budgets in the Army Corps of Engineers and Bonneville Power Administration are producing important new understanding, but commercial applications are unlikely because of pressures from industry deregulation and environmental regulation.

Recent Success

- TVA's Lake Improvement Plan has demonstrated that improved turbine designs can be implemented with significant economic and environmental benefits.
- EPRI's CompMech Program has demonstrated multimillion dollar cost savings in regulatory compliance by applying new assessment technology for the New England Power Company.

Commercialization and Deployment

- Voith Hydro and TVA have established a limited partnership to market environmentally friendly technology at hydropower facilities. Their products were developed in part by funding provided by DOE and the Corps of Engineers, as well as private sources.
- Flash Technology is developing strobe lighting systems to force fish away from hydropower intakes and to avoid entrainment mortality in turbines.

Potential Benefits and Costs

Carbon Reductions

- The current trend is to replace hydropower with electricity from fossil fuels. This trend leads to increases in GHG and should be reversed.
- Hydropower generation produces zero carbon emissions and, if fossil fuels were used as the alternative energy source, would displace 5–10 MtC/year in 2010, 10–15 MtC/year in 2020, and 15–30 MtC/year in 2030.

RD&D Expenditures

- DOE budgets would have to increase from the current level of \$1M/year up to \$10M/year and remain at that level through 2010. Thereafter, through 2030, \$1M/year would be needed.

Market

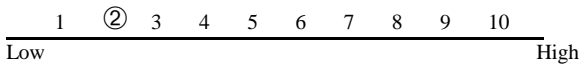
- Advanced hydropower products can be applied at more than 80% of existing hydropower projects (installed conventional capacity is now 78 GW); the potential market also includes 15–20 GW at existing dams without hydropower facilities (i.e., no new dams required for development) and about 30 GW at undeveloped sites that have been identified as suitable for new dams.

Nonenergy Benefits and Costs

- There would be significant environmental benefits from installing advanced hydropower technology, including enhancement of fish stocks, tailwater ecosystems, and recreational opportunities. These benefits would occur because the advanced technology reverses adverse effects of the past.
- Additional benefits would come from the protection of a wide range of ancillary benefits that are provided at hydropower projects but are at extreme risk of becoming lost in the new deregulated environment.

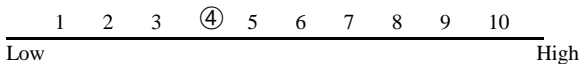
Risk Factors

Technical Risk



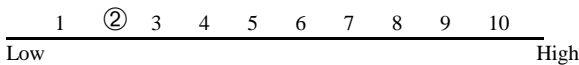
- Existing technology and research methods need to be applied to environmentally oriented objectives.

Commercial Risk



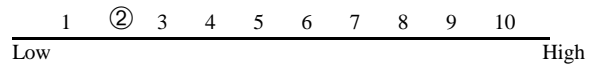
- Industry maintains there is a very large market for improved environmental management techniques at hydropower projects in the United States and abroad; however, the barrier of high capital costs for installation would have to be overcome.

Ecological Risk



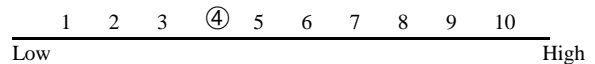
- The new hydropower technology will eliminate adverse environmental effects—the net programmatic ecological impacts are positive.

Human Health Risk



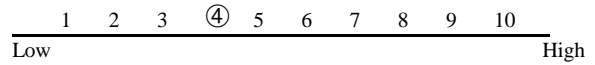
- Changes in project design and operation would involve the same risks as any comparable construction activity.

Economic Risk



- Public acceptance of multipurpose water projects, including hydropower, should be forthcoming if environmental protection can be demonstrated.

Regulatory Risk



- Regulatory and resource agencies are willing to participate in testing programs and accept new technologies if they are proven.

Key Federal Actions

- Reverse declining research investments in industry and federal government caused by industry deregulation and other economic/regulatory pressures on the hydropower industry.
- Take a leadership role in technology transfer to ensure that new hydropower technologies reach commercial applications and are accepted by environmental regulators, natural resource managers, and the public.
- Build partnerships among industry, regulators, and natural resource agencies to minimize local environmental effects of hydropower while realizing global benefits of increased GHG-free generation.

8.4 SOLAR PHOTOVOLTAICS

Technology Description

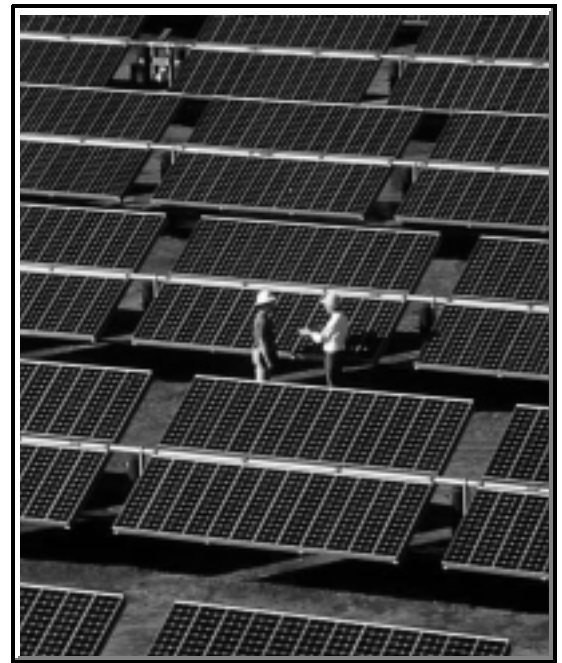
Photovoltaic (PV) devices convert sunlight to electricity without moving parts and without producing fuel wastes, air pollution, or GHGs. A PV-generating station 140 km by 140 km in area at an average solar site in the United States could generate all of the electricity needed in the country (2.5×10^6 GWh/year), assuming a system efficiency of 10% and an area packing factor of 50% (to avoid self-shading). A well-planned transition to solar PV for electricity and transportation could make serious inroads in reducing CO₂.

System Concepts

- Flat-plate PV arrays use global sunlight; concentrators use direct sunlight. Modules are mounted on a stationary array or on single- or dual-axis sun trackers. Arrays can be ground-mounted or on all types of buildings and structures. PV dc output can be conditioned into grid-quality ac electricity, or dc can be used to charge batteries or to split water to produce H₂.
- PV systems are expected to be used in the United States for residential and commercial buildings, peak power shaving, and intermediate daytime load following; with electric storage and improved transmission, systems could be used for dispatchable electricity and H₂ production in the future.
- Most locations in the United States and worldwide have enough sunlight to make PV useful locally.

Representative Technologies and Status

- Wafers of single-crystal or polycrystalline silicon (cells: 24% efficiency; commercial modules: 13%–15%). Si modules dominate the PV market and currently cost about \$3/W_p.
- Thin-film materials (e.g., amorphous silicon, copper indium diselenide, cadmium telluride, polycrystalline silicon, and dye-sensitized cells) (cells: 12%–18%; commercial modules: 5%–7%; best prototypes modules: 9%–11%). A new generation of thin-film PV modules is going through a rapid and high-risk commercialization period.
- High-efficiency single-crystal Si and multijunction GaAs-alloy cells for concentrators (cells: 25%–30% efficient; commercial modules: 15%–17%).
- PV systems currently sell for about \$5–\$10/W_p, including support structures, power conditioning, and land.



Current Research, Development, and Demonstration

RD&D Challenges and Goals

- Improve fundamental understanding of materials, processes, and devices to provide a technology base for advanced PV options.
- Optimize PV cell materials, cell designs, and modules; scale up laboratory cell results to product size (10^4 increase in area).
- Validate new module technologies outdoors and in accelerated testing (goal: 30 years outdoors).
- Improve and invent new low-cost processes and technologies; reduce module and balance-of-systems manufacturing costs.
- Substantial technical risks associated with first-time manufacturing for advanced technologies.
- Develop and validate new, lower-cost systems hardware and integrated applications.
- Meet cost-competitive goal of manufacturing and installing PV systems at under \$1/W_p.

RD&D Activities

- DOE maintains the most important RD&D program in the United States, with funding levels during the 1990s between \$60 and \$90M; FY 1997 was \$60M.
- DOD has some funding through special programs in which PV has a role supplying power for military systems.
- NASA has some research funds for PV used for space power. This program has dwindled over the last decade, but advanced PV has become even more important for space missions (e.g., the high-performance GaAs cells on the Sojourner on Mars).
- Japan and Europe have significant funding for PV. The Japanese level is about \$200 million annually.
- U.S. PV businesses are not yet profitable and are unable to fund their own advanced research.
- Some semiconductor and integrated circuit materials R&D, flat-panel displays, and production technology developments provide information for PV development, particularly for silicon-based PV technology.

Recent Successes

- Because of private-public DOE/NREL programs, such as the Thin Film Partnership, U.S. PV technology leads the world. Another partnership, the PVMaT manufacturing program, has resulted in industry cost reductions of 25% and facilitated a doubling of manufacturing capacity.
- Two thin-film plants by United Solar and Amoco-Enron Solar began production in 1997. Others are expected in the next 2 years. Thin-film PV has been the focus of the DOE/NREL efforts of the last decade, and these particular advances were initially funded under the Amorphous Silicon Research Project.
- During the last 2 years, *world record* solar cell sunlight-to-electricity conversion efficiencies were set by federally funded universities, national laboratories, or industry in amorphous silicon (12%), polycrystalline Si (19%), and copper indium gallium diselenide (18%).

Commercialization and Deployment

- About 120 MW of PV were sold in 1997 (about \$1 billion worth); total installed PV is about 500 MW. The U.S. world market share is about 40%. Annual market growth for PV is 25% as a result of reduced prices and successful global marketing. Hundreds of applications are cost-effective for off-grid needs; the largest market growth area in the United States and internationally. More than two-thirds of U.S.-manufactured PV is exported. There are about 75 PV module manufacturers worldwide, and hundreds of vendors sell systems. About 25 U.S. companies produce commercial PV. Japan and Europe have strong, competitive PV infrastructures and sales.

Potential Benefits and Costs

Carbon Reductions

- A GW_p of PV produces about 1600 GWh/year of electricity in an average U.S. solar location (Kansas). Assuming the same carbon content as the U.S. utility mix (160 MtC/GWh), a 1- GW_p PV system would avoid 8 MtC during its 30-year lifetime. PV grew at a 25% rate in 1997. At an assumed steady 20% growth rate, about 50 GW_p would be installed in the United States by 2030; assuming a higher early rate ramping down to a much lower, sustainable rate, over 200 GW_p would be installed by 2030. This projected range of PV installations would save up to 2 MtC/year in 2010, 5–10 MtC/year in 2020, and 15–55 MtC/year in 2030.

RD&D Expenditures

- DOE PV budgets were \$60M in FY 1997. The estimated U.S. budget needed to accelerate PV would be about \$150M/year for R&D during the two decades to 2010 and 2020; this could be reduced, as PV reaches maturity, to about \$100M/year for R&D during the decade to 2030. In addition to the R&D activities, substantial support must be given to market assurance activities during the next two decades.

Markets

- Electricity economically provided for billions of people worldwide who do not have electricity.
- U.S. markets: retail electricity for residential and commercial buildings; distributed utility systems for grid support; peak-shaving and other high-value daytime uses. Electric and H_2 storage: dispatchable electricity, electric car charging stations, and hydrogen production for portable fuel.

Nonenergy Benefits and Costs

- PV systems operate with zero emissions. PV is modular: installation can be sized from a few watts to many gigawatts. Maintenance needs are low because of the lack of moving parts and the durable components, which is good for uses in developing countries. PV provides power for telecommunications in developing countries and will improve the standard of living for millions who lack electricity, contributing to reduced rural-to-urban population shifts. The taxpayer's investment in RD&D could be recouped through job creation, expanded tax revenues, economic development (including improved balance of payments with our international competitors), and improved environmental quality.

Risk Factors

Technical Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- Challenges related to materials properties, low-cost but high-quality film deposition processes, diagnostics.
- Advanced storage and large-scale wheeling strategies (to compensate for PV intermittence) are not well-developed.

Commercial Risk

1 2 3 4 5 ⑥ 7 8 9 10

Low High

- Sunlight is intermittent.
- Companies need market assurance to invest large sums in plant capacity expansion.
- Rapid increases in capacity may create unexpected issues.

Ecological Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- Land use and disposal or recycling of microscopic amounts of heavy metals in some systems

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- In-plant safety issues are familiar from the semiconductor industry.
- Risk reduction: poor, rural communities in developing countries will achieve a higher standard of living and health.

Economic Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Public perception is very favorable.
- Some risk that cost goals will not be met.

Regulatory Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Practical issues of electrical standards and codes (PV stand-alone and grid-tied products).
- Utility resistance to consumers selling retail electricity back to them ("net metering").
- Uncertainty stemming from utility deregulation.

Key Federal Actions

- Support R&D to improve performance and reduce costs and to build a scientific base for advanced PV technologies.
- Provide R&D funding to reduce the risk of first-time manufacturing for high-potential PV technologies.
- Level the regulatory playing field and ensure sustained market growth to catalyze private investment.

8.5 GEOTHERMAL ENERGY

Technology Description

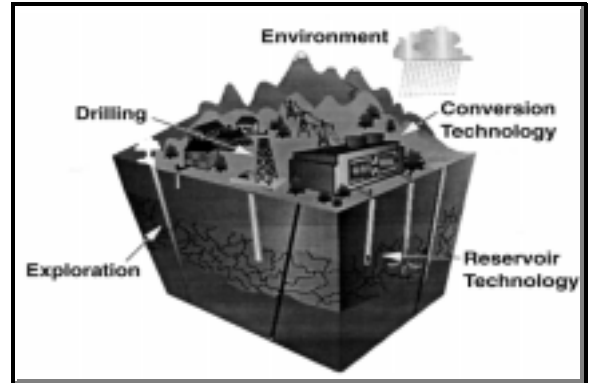
Geothermal energy is energy from within the earth. Hot water and steam are used to produce electricity or applied directly for space heating and industrial processes. Geothermal heat pumps (GHPs) use the thermal mass of the earth as a heat sink for air conditioning and heating.

System Concepts

- Geophysical, geochemical and geological exploration locate reservoirs to drill, including highly permeable hot reservoirs, shallow warm groundwater, hot dry rock masses, highly pressured fluids, and magma.
- Well fields and distribution systems allow the hot fluids or secondary fluids to move to the point of use, and possibly back to the earth.
- Utilization systems apply the heat directly, convert it to another form of energy such as electricity, or cool efficiently by dumping heat back into the earth.

Representative Technologies

- Exploration technologies for the identification of fractures and geothermal reservoirs; drilling, reservoir testing and modeling to optimize production and predict useful lifetime; electric turbines using natural steam or hot water flashed to steam, or binary conversion systems to produce electricity from water not hot enough to flash.
- Direct applications to use the heat from geothermal fluids without conversion to electricity.
- GHPs that use a shallow ground loop to move heat between the earth and heating/air conditioning systems.



Technology Status/Applications

- The United States has a resource base capable of producing >25 GW of electricity at 3.5–15.0¢/kWh.
- Hydrothermal reservoirs are being used to produce electricity with an on-line availability of 97%; advanced energy conversion technologies are being implemented to improve plant thermal efficiency.
- Direct-use applications are successful, but require co-location of a quality heat source and need.
- GHPs produce 20 to 40% reductions in electricity demands for many residential and governmental installations. They compete favorably with air-source heat pumps and replace gas furnaces in some areas.

Current Research, Development, and Demonstration

RD&D Goals

- By 2010, make geothermal cost-effective so that it provides about 10 GW on line, enough electricity for 12 million homes; by 2020, develop new approaches to utilization that increase the domestic reserve base by a factor of 10; by 2030, bring new approaches on line.
- By 2020, displace 100,000 barrels of oil (equivalent; 0.5 quads) per year with direct heat use and GHP. Ensure continued growth in use.

RD&D Challenges

- Develop improved methodologies for predicting reservoir performance and lifetime.
- Find and characterize underground permeability and develop low cost, innovative drilling technologies.
- Reduce capital and operating costs and improve the efficiency of geothermal conversion systems.
- Demonstrate heat recovery methods that allow the use of geothermal areas that are deeper, cooler, less permeable, or dryer than those currently considered as reserves.

RD&D Activities

- DOE EERE spends \$30M per year, promoting collaborations of laboratories, universities, states, and industry. Industry provides access to data, equipment and geothermal materials, and matching funds. Related studies are supported by DOE-OBES and FE, although the amounts have not been estimated. The international research budget is much higher, involving Japan, Iceland, Italy, Mexico, New Zealand, France, and others.

Recent Success

- Completion—with industry and federal, state, and local agencies—of an injection research project and water replacement pipeline that will increase production and extend the lifetime of the Geysers Geothermal Field.
- New equipment increasing thermal efficiency and reducing operating and maintenance costs of geothermal power plants, including demonstrations of metastable turbine expansion, improved condenser packing materials, off-stream gas compressor, new materials, and the rolling float meter.

Commercialization and Deployment

- Hydrothermal reservoirs produce about 2100 MW in the United States and about 6000 MW worldwide. Direct-use applications produce about 400 MW_t in the United States. There were 120,000 GHPs in the United States with an installed capacity of over 4000 MW_t in 1996, and that number is increasing by 25% per year. United States companies generate 200 to 300 new MW overseas each year.
- Costs are marginally competitive at today's natural gas prices, and investment is limited by uncertainty in prices, long-term viability of production systems, and delay between investment and return.

Commercialization and Deployment (continued)

- Improvements in cost and accuracy of resource exploration and characterization can lower the electricity cost; demonstration of new resource concepts, such as heat mining, low-temperature use, or deep systems, would allow a large expansion of U.S. use of hydrothermal when economics become favorable. Direct applications can be expensive unless users are located above a geothermal reservoir. GHPs reduce lifetime costs relative to air source heat pumps, but initial cost and consumer uncertainty limits deployment.

Potential Benefits and Costs

Carbon Reductions

- Hydrothermal electric and most GHPs displace the average electric power generating mix, which typically generates 160 gram carbon/ kWh. GHPs also displace inefficient local heating units that produce >14 MtC/quad. Direct heat displaces a mix of electric and gas-thermal. All of these methods have on-line records of 95% or more, reducing the use of carbon-producing backup generation and storage facilities. In total, geothermal energy is expected to reduce GHG emissions by 5–10 MtC/year in 2010, 5–20 MtC/year in 2020, and 5–30 MtC/year in 2030.

RD&D Expenditures

- To achieve the RD&D progress described, RD&D expenditures need to increase from the current \$30M/year to an average \$62M/year in 2000–2010, \$53M/year in 2010–2020, and \$31M/year in 2020–2030.

Market

- Geothermal will continue production of existing plants (2.1 GW) and be used for new construction (348 GW by 2030). Direct heat and GHPs will replace existing systems and will be new systems in a huge market.

Nonenergy Benefits and Costs

- The energy production per land area is high for a low-carbon technology. Byproducts are limited to relatively benign steam plumes, waste water, and sludge. Fluid effluents may be mined for minerals or injected back into the reservoir. Some plants using injection have zero emissions. Geothermal plants spend more for personnel and less for fuel than do conventional plants.

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Incremental improvements can reduce the risks of exploring and drilling, unpredictability of reservoir performance, and degradation of efficiency. Advanced reservoir utilization strategies have a low to moderate technical risk.

Commercial Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- These technologies require the confidence of lenders, power generators, heating and air conditioning installers, and project planners in order to be accepted.

Ecological Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Although the potential for modification of natural geysers and features limits its use in very scenic areas, geothermal power produces few emissions and little waste and requires minimal land area. Enhanced injection may require new water sources.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- In general, emissions from geothermal facilities are much less than from fossil fuel plants. Some fields must abate hydrogen sulfide and dispose of residues in hazardous waste sites.

Economic Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- Because its costs cannot be lowered much below the price of natural gas, geothermal power for electric production will continue to be vulnerable to cost reductions for competing fuels.

Regulatory Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- The principal regulatory risk is that associated with the regulatory changes caused by deregulation of the utility industry. However, several industry analysts say that this will produce a net positive effect.

Key Federal Actions

- Support incremental and longer-term R&D as outlined above.
- Ensure that environmental externalities are included in the costs of energy production and use.
- Demonstrate nonelectric geothermal technologies, and educate planners, homeowners, regulators, and suppliers about their merits.
- Develop approach to support U.S. industries that compete with government-supported consultants and developers overseas.
- Continue to allow access to federal lands for geothermal development.

8.6 SOLAR THERMAL ELECTRIC AND BUILDINGS

Technology Description

Solar thermal systems concentrate solar energy 50 to 5000 times to produce high-temperature thermal energy, which is used to produce electricity for distributed or bulk generation or heat for building and industrial process applications.

System Concepts

- In solar thermal electric systems, large, highly reflective sun-tracking mirrors produce temperatures of 400 to 800°C in the working fluid of a receiver; this heat is used in conventional heat engines (steam or gas turbines or Stirling engines) to produce electricity at system solar-to-electric efficiencies of up to 30%.
- In solar thermal buildings systems, compound parabolic concentrating collectors and nonconcentrating technologies convert solar energy into lower temperature heat at the point of use, usually for domestic hot water and space heating.

Representative Technologies

- A parabolic trough system focuses solar energy on an oil-filled receiver to collect heat to generate steam to power a steam turbine. When the sun is not shining, steam can be generated with fossil fuel to meet utility needs. Plant sizes can range from 10 to 100 MWe.
- A power tower system (see photo) uses many large heliostats to focus the solar energy onto a tower-mounted central receiver filled with a molten-salt working fluid that produces steam. The hot salt can be stored extremely efficiently to allow power production to match utility demand even when the sun is not shining. Plant size can range from 30 to 200 MWe.
- The dish/engine system uses a dish-shaped reflector to power a small Stirling or Brayton engine/generator mounted at the focus of the dish. Dishes are 10–25 kW in size and can be used individually or in small groups for remote or village power, or in larger (1–10 MWe) clusters for utility applications, including end-of-line support. They are easily hybridized.
- Building systems use flat-plate or evacuated tube collectors, concentrating evacuated tube or parabolic trough collectors, or unglazed transpired collectors to heat water or air for building applications.



Technology Status/Applications

- Nine parabolic trough plants, with a rated capacity of 354 MWe, have been operating in California since 1985. Trough system costs of about 12¢/kWh have been demonstrated commercially.
- Solar Two, a 10-MWe pilot power tower with 3 hours of storage, is providing all the information needed to scale up to a 30–100 MW commercial plant.
- A number of prototype dish/Stirling systems are currently operating in Colorado and Spain. High levels of performance have been established; durability remains to be proven, although some systems have operated for over 10,000 hours.
- Typical residential systems use roof-mounted flat-plate collectors combined with storage tanks to provide 40% to 70% of residential water heating requirements at efficiencies of 35%. Typical systems cost \$2500 to \$3500 and achieve payback periods of 5 to 15 years vs electric resistance water heaters and 20 to 30 years vs gas water heaters.
- Industrial systems and large commercial systems using unglazed transpired collectors for preheating ventilation air have achieved payback periods of well under 10 years. A transpired collector is a thin sheet of perforated metal that absorbs solar radiation and heats fresh air drawn through its perforations.

Current Research, Development, and Demonstration

RD&D Goals

- RD&D goals are to reduce costs of solar thermal systems to 5 to 8¢/kWh with moderate production levels within 5 years, and below 5¢/kWh at high production levels in the long term.

RD&D Challenges

- RD&D efforts are targeted to improve performance and lifetime, reduce manufacturing costs with improved designs, provide advanced designs for long-term competitiveness, and address barriers to market entry.
- Improved manufacturing technologies are needed to reduce the cost of key components, especially for first-plant applications where economies of scale are not yet available.
- Demonstration of Stirling engine performance and reliability in field use are critical to the success of the dish/engine systems.

RD&D Activities

- Key DOE program activities are targeted to support the next commercial opportunities for these technologies, demonstrate improved performance and reliability of components and systems, reduce energy costs, develop advanced systems and applications, and address non-technical barriers and champion solar thermal power.
- FY 1997 DOE funding levels were about \$25M. Several European countries and Israel have programs 50 to 80% of this size.

Recent Success

- The 10-MW Solar Two pilot power tower plant is operating successfully near Barstow, California.
- Operations and maintenance costs have been reduced through technology improvements at the commercial parabolic trough plants in California by 30%, saving plant operators \$50M.

Commercialization and Deployment

- Parabolic troughs have been commercialized and nine plants (354 MW total) have operated in California since 1985.
- Successful operation of Solar Two will provide the basis for a partnership to provide the first 30–100 MW power tower plant.
- Dish/Stirling systems are expected to be available by 2000, after deployment and testing of 1 MW (40 systems) over the next 2 years.
- About 1.2 million solar domestic hot water systems have been installed in the United States; 14,000 installations per year (\$47M).
- Ventilation preheat systems using unglazed transpired collectors have made significant progress in commercial/industrial markets with several dozen large-scale projects currently in operation.
- The World Bank’s “Solar Initiative” is pursuing solar thermal technologies for less-developed countries. The World Bank considers solar thermal as a primary candidate for Global Environment Facility funding, which could total \$1B to \$2B for projects over the next 2 years.

Potential Benefits and Costs

Carbon Reductions

- Carbon reductions are estimated to be 1–5 MtC/year in 2010, 5–15 MtC/year in 2020, and 15–30 MtC/year in 2030.

RD&D Expenditures

- Federal R&D funds for solar thermal electric of \$22M in FY 1997 have been matched by industry cost sharing of about \$15M/year. Federal R&D funds for solar thermal buildings have been about \$3M/year.
- DOE support of RD&D has been required because of the specialized technology development, the significant remaining time to market, and barriers (real and perceived) to market penetration. The federal STE program provides expert technical support as well as a catalyst/facilitator role for participation of utilities and manufacturers to assist in driving system costs down.
- Required incremental RD&D expenditures for solar thermal electric are estimated to be \$30M/year through 2010 and \$10M/year through 2030.
- Required RD&D expenditures for solar thermal buildings is estimated to be \$37M/year through 2010, \$31M/year through 2020, \$28M/year through 2030.

Market

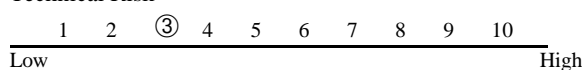
- STE technologies provide firm, nonintermittent electricity generation (peaking or baseload capacity) when coupled with storage.
- Solar building technologies will reduce daytime peak electricity requirements and heating season fuel.

Nonenergy Benefits and Costs

- Solar thermal building systems can enhance national security by reducing vulnerability to oil supply disruption.
- Solar thermal technologies are environmentally benign with essentially no emissions.
- A near term to mid-term opportunity exists to build production capacity in the United States for both domestic use and international exports.

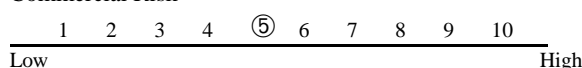
Risk Factors

Technical Risk



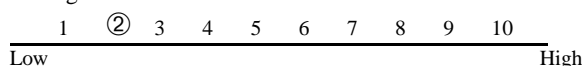
- Parabolic troughs are a proven technology at commercial scale with no significant technical risk; others are expected to be similar.
- Performance of the Stirling engine is crucial for dish systems.

Commercial Risk



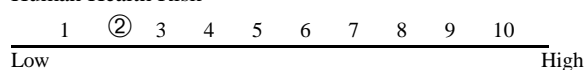
- Cost-competitiveness depends on costs of alternatives in the United States, but specific off-grid applications exist internationally.

Ecological Risk



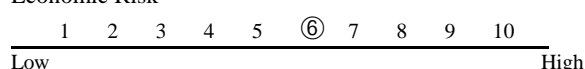
- The only significant impact is use of desert-type land, which is less than equivalent land use of coal and hydro power.

Human Health Risk



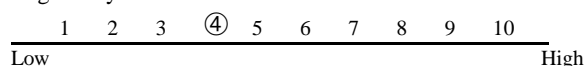
- None, other than those for workers associated with any utility type power plants (e.g., machinery, hot fluids).

Economic Risk



- Capital-intensive nature of the technology requires up-front investment.

Regulatory Risk



- Utility deregulation emphasis on low cost is a negative, but green power sales options could be valuable.

Key Federal Actions

- Federal support of the first few plants (through buy-downs, power purchase contracts, production credits) would overcome the problem of building the first plants to get costs down until production goes up. The Million Solar Rooftops and ReCAST initiatives are examples.
- Federal support of utility deregulation that would encourage the marketing of “green power” could enhance early solar thermal generation.
- Tax code changes that would not penalize capital intensive projects (which are currently taxed several times higher than fuel-intensive projects) have the potential to dramatically enhance the financial viability of early plants.

8.7 BIOMASS TRANSPORTATION FUELS

Technology Description

Biomass transportation fuels, or biofuels, are liquid transportation fuels made from cellulosic plant biomass (fibrous materials, as opposed to starch such as corn) that can be used to displace petroleum used in internal combustion engines. In the future, biofuels such as methanol, ethanol, and hydrogen will play a role as energy storage media in fuel cells.

System Concepts

- Biomass for conversion to liquid fuels can be obtained from wastes, grass, or tree crops grown for energy production, and coproduction and harvesting of biomass feedstocks with other plant products. Growth of microalgae using CO₂ from fossil fuel combustion is also a potentially large feedstock for fuel production.
- The waste products from manufacturing biofuels (mainly lignin) can be used to generate electricity; enough electricity can be generated to power the plant and return an equal amount to the grid.

Representative Technologies

- Biological production of biofuels involves hydrolysis of fibrous biomass to form soluble sugars, using enzymes or acid catalysts, followed by microbial conversion of sugars to ethanol.
- Thermochemical production of biofuels involves gasification to form synthesis gas, from which methanol and other products are made, or pyrolysis to form diesel fuel substitutes.
- The use of natural oils from microalgae also has both biological and thermochemical routes that need to be explored.

Technology Status/Applications

- By 2000, ethanol made from low-cost cellulosic feedstocks will augment corn ethanol (current price ~\$1.20/gal) for use as an oxygenate or octane enhancer, but the greatest benefit for reducing GHG emissions is to replace conventional bulk fuels (currently ~\$0.65/gal). Future R&D advances have clear potential to lower the cost of biofuels, with commensurately larger fuel markets becoming accessible. The central technological challenge is to advance biomass processing to a level of maturity comparable to that of the existing petroleum industry. Development of a large biomass resource basis is another important challenge.



Current Research, Development, and Demonstration

RD&D Goals

- By the year 2000, demonstrate a biomass waste-to-fuels process with an industrial partner.
- By the year 2005, demonstrate biomass production and its conversion to fuels.
- By the year 2010, demonstrate biofuels technologies that compete with petroleum for direct fuel replacement.

RD&D Challenges

- Biological processing: low-cost production of cellulases, microorganism development for consolidated processing, advanced pretreatment and hydrolysis process, coproduct production and recovery.
- Thermochemical processing: improved understanding of reaction fundamentals, reaction engineering to improve performance, new catalyst development.
- Biomass production: crop development for improved productivity and robustness; improved cultivating, harvesting, and collection technologies; analysis of long-term land availability and crop economics.

RD&D Activities

- Industrial partnerships for demonstrating waste biomass-to-ethanol technology.
- Feedstock production research (primarily on switchgrass and hybrid poplar).
- Technology for converting cellulosic materials to ethanol (R&D on chemical pretreatment, genetic engineering of new enzymes and organisms, and process development).
- FY 1997 DOE EERE funding was \$23M/year. Supportive activities occurred through the DOE ER, USDA, and other agencies, but amounts were not estimated.

Recent Success

- Breakthroughs in genetically engineered microorganisms capable of fermenting the broad range of sugars found in biomass. These advances have led to patents and licensing of organisms to the corn ethanol industry to enable fermenting of the cellulosic waste portions of the corn plant, and other potential cellulosic ethanol producers, as well as an "R&D 100" award.
- Successful continuous operation of a pilot-scale ethanol process using low-value residual biomass. This testing was done with an industrial partner at DOE's one-of-a-kind user facility for pilot-scale production of ethanol.

Commercialization and Deployment

- Fuel-grade ethanol from cellulosic biomass is not yet commercial. Fuel-grade ethanol from corn is a 1.5-billion-gal/year industry (\$2B/year in sales) in the United States. Ethanol is used primarily as a fuel extender (gasohol) and secondarily as an oxygenate and an additive for reformulated gasoline.
- Large-scale displacement of petroleum will rely primarily on cellulosic materials. Starch crops such as corn will play an important transitional role.

Potential Benefits and Costs

Carbon Reductions

- The CO₂ released when biofuels are used is recycled by plants, resulting in net carbon emissions approaching zero; displacing a unit of energy from gasoline with a unit of energy from ethanol in light-duty vehicles results in a 90% reduction in carbon emissions. Similar reductions can be expected from such biomass fuels as methanol, biodiesel, and other biofuels. Although there are several potential different biofuels, carbon reduction estimates were made only on ethanol using switchgrass as a feedstock at 10% and 95% blends, compared with reformulated gasoline. Carbon reduction estimates assume a market penetration for these blends of 4 billion gal in 2010, 9.5 billion gal in 2020, and 9.5 billion gal in 2030. With the low projected price of gasoline, and without extra policy incentives, neat ethanol was not considered cost-effective enough to use as a transportation fuel during this 30-year period. Calculations included carbon reductions from biomass-generated electricity returned to the grid from ethanol plants.
- Carbon reductions were estimated as 5–15 MtC/year in 2010, 20–30 MtC/year in 2020, and 20–35 MtC/year in 2030.
- **RD&D Expenditures**
- Funding of around \$23M/year has been spent in FY 1996 and FY 1997, supporting research by national laboratories, universities, and industry partners.
- Achieving the economical carbon reduction costs described above requires significant funding increases. The technology improvements required call for quickly ramping up the research program from its current level, averaging \$75M/year during 2000–2010. During 2010–2020, an average of \$100M/year would be needed for work on biomass production to ensure a large and cost-effective resource base for fuel production by 2020. Fuel production technologies must close the cost gap between petroleum and biomass-derived fuels. During 2020–2030, \$50M/year would be required.

Market

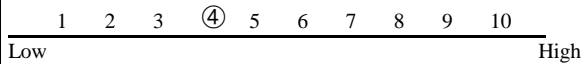
- Biofuels can provide renewable substitutes for both gasoline and diesel fuel, supporting the energy needs of both the light-duty and the heavy-duty market. Diesel fuel usage is expected to grow at a faster rate than gasoline usage. These two uses represent almost a quarter of total energy consumption in the United States.

Nonenergy Benefits and Costs

- Biofuels provide opportunities for agriculture and rural America. Export of U.S. biofuels technology provides a lever for maintaining U.S. economic and technological leadership in the global marketplace. Biofuels will also address problems of urban air pollution.

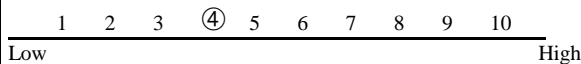
Risk Factors

Technical Risk



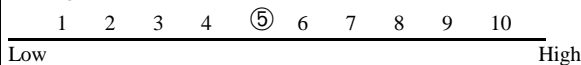
- Technology improvements require a major R&D effort. The rate and extent of such funding will determine the contribution that biofuels can have.

Commercial Risk



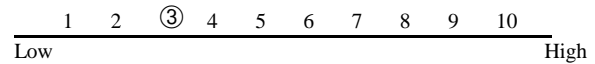
- Infrastructure compatibility, end-use flexibility, and existing corn-based biofuels industry are key advantages. Uncertainty of tax incentives in the near term could be an impediment.

Ecological Risk



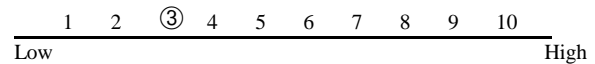
- Land use impacts such as erosion could be positive or negative, depending on management choices.

Human Health Risk



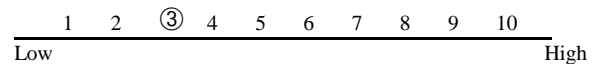
- Biofuels are relatively nontoxic. Worker safety would require the same precautions as current agricultural practices.

Economic Risk



- Only modest investments in infrastructure are needed.

Regulatory Risk



Key Federal Actions

- Expand funding and focus on core technology improvement.
- Enhance collaboration among national laboratories, academia, and other government research sponsors.
- Focus industry partnerships on common technical obstacles for biomass-derived fuels and chemicals.
- Stabilize federal tax policies that recognize benefits of alternative fuels.
- Seek to resolve key analytical uncertainties (long term costs, land availability, life cycle benefits and impacts).

8.8 SOLAR ADVANCED PHOTOCONVERSION

Technology Description

Photoconversion technology encompasses sunlight-driven quantum-conversion processes (other than solid-state PVs) that lead to the direct and potentially highly efficient production of fuels, materials, chemicals, and electrical power from simple renewable substrates such as water, CO₂, and molecular nitrogen. This technology has the potential to eliminate the need for fossil fuels by substituting renewable sources and conversion processes that are either carbon neutral (any carbon generated is reused during plant growth) or carbon free (e.g., hydrogen from water). These technologies also can convert CO₂ into liquid and gaseous fuels via processes that are often termed biomimetic or artificial photosynthesis.

System Concepts

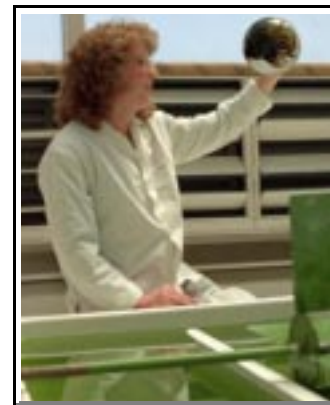
- Photoconversion processes directly use solar photons to drive biological, chemical, or electrochemical reactions to generate electricity, fuels, material, or chemicals.
- System components include biological organisms or enzymes, semiconductor structures (photoelectrochemical cells, colloids, nanocrystals, or superlattices), biomimetic molecules, dye molecules, synthetic catalysts, or combinations of the above.

Representative Technologies

- Elements of this future solar technology include photobiological, photochemical, photoelectrochemical, photocatalytic, and dark catalytic processes for energy production.
- Photoconversion technologies can result in electrical power production; hydrogen production and utilization; biodiesel, organic acid, methane, and methanol production; bioplastics; the removal of CO₂ from the atmosphere as a consequence of photoreduction of CO₂ to fuels, materials, and chemicals production; atmospheric nitrogen fixation (independent of natural gas); and waste or biomass utilization upon photoconversion to fuels, materials, or chemicals. Most of these technologies are at early stages of research, but some are at the development level, and a couple are commercial (those that produce high-value products).

Technology Status/Applications

- Power production: dye-sensitized, nanocrystalline, titanium dioxide semiconductor solar cells are at the 8–11% efficiency level and are potentially very cheap. In contrast to solid-state PV solar cells, light is absorbed by dye molecules in contact with a liquid rather than solid-state semiconductor materials. Novel photoelectrochemical cells with integrated fuel cells and in situ storage for 24-h solar power have been demonstrated at 6–7% efficiency in 4 × 8 ft panels (Texas Instruments system), and photochargeable batteries that include electrochemical storage have been demonstrated with 24-h power output. Hot-carrier photoconversion technology for increasing solar conversion efficiencies (theoretical efficiency limits of 65%) is making progress. The term “hot carrier” refers to electrons initially excited by light, when they have energy higher than their equilibrium levels. This excess energy is given off in the first fraction of a second as heat, and hot-carrier technology attempts to capture this lost heat as useful electricity.
- Fuels production: Photoelectrochemical and photobiological processes that will lead to hydrogen production from water or gasified biomass are at the early stages of research and making good progress; biodiesel, methane, and methanol production from water, waste, and CO₂ are at various stages of R&D; and fuels, such as methanol, produced by the direct electrocatalytic or photocatalytic reduction of CO₂, are at the early fundamental research stage. Electrocatalytic concentration of CO₂ from the atmosphere is being studied as well; it is of interest to persons involved in atmospheric controls in small spaces (i.e., submarines) and has potential for removing CO₂ from the atmosphere in the future.
- Materials and chemicals production: producing materials and chemicals from CO₂ and/or biomass will reduce CO₂ emissions compared with the fossil fuels used currently.
- Photobiological production of pigments (e.g., astaxanthin), health foods, nutritional supplements (e.g., omega-3 fatty acids), protein, and fish food is commercial. Production of biopesticides and pharmaceuticals is under development. Production of commodity chemicals such as, but not limited to, glycerol, hydrogen peroxide, and bioemulsifiers is possible. Photocatalytic production of specialty or high-value chemicals has been demonstrated.



Current Research, Development, and Demonstration

RD&D Goals

- Most photoconversion technologies are at the fundamental research stage where technical feasibility must be demonstrated before cost and performance goals can be assessed. Minimum solar conversion efficiencies of 10% are generally thought to be necessary before applied programs can be considered. Cost goals need to be competitive with projected costs of current technologies.
- Electrical power and high-value chemicals applications are either currently commercial or will see dramatic growth over the next 5 to 10 years. Large-scale power production should begin about the year 2010. Materials and fuels production will begin in the 2010–2020 time frame and commodity chemicals production in the 2020–2030 time frame.

RD&D Challenges

- Develop the fundamental sciences in multidisciplinary areas involving theory, mechanisms, kinetics, biological pathways and molecular genetics, natural photosynthesis, materials (semiconductor particles and structures), catalysts and catalytic cycles, and artificial photosynthesis components. The fundamental science is needed to underpin the new photoconversion technologies.
- Maintain critical mass research groups in vital areas long enough for sustained progress to be made.

RD&D Activities

- Basic research activities are currently being funded at a level of \$10–\$15M/year from the DOE Office of Basic Energy Research.

Recent Success	
<ul style="list-style-type: none"> Dye-sensitized nanocrystalline semiconductor solar cells have been demonstrated as power sources in small niche markets. Commercial interest is very high since they also can be configured to produce hydrogen. Scientific breakthroughs over the past 5 years have been made in microbial and enzymatic R&D, natural photosynthesis, semiconductor nanostructure and superlattice understanding, CO₂ catalysis, and energy and electron transfer in artificial donor/acceptor molecules. 	
Commercialization and Deployment	
<ul style="list-style-type: none"> Large-scale algal ponds are producing high-value chemicals on a commercial basis using photobiological processes. As an example, the current astaxanthin market is \$180M per year and will rise to \$1B in 5 years. Astaxanthin, a pigment synthesized from petroleum, is used as a coloring agent in the poultry and salmon industries. Algal production of the pigment just started in Hawaii and is replacing the fossil version for health and environmental reasons. SMH Corporation (a European company) has just started to sell dye-sensitized, nanocrystalline cell-powered watches. The market is estimated to be 100 million units. 	
Potential Benefits and Costs	
<p>Carbon Reductions</p> <ul style="list-style-type: none"> Photoconversion processes can ultimately replace (or displace) all fossil fuels as a source of energy, materials, and chemicals. The time scale is uncertain, but significant impacts on reduction of CO₂ release could begin in the next 30 to 50 years. It should be emphasized that solar photoconversion produces no CO₂ and can in fact remove CO₂ from the atmosphere. <p>RD&D Expenditures</p> <ul style="list-style-type: none"> A significant level of basic research activities in solar photoconversion is currently being funded by ER (BES—chemical sciences, material sciences, and energy biosciences) (estimated level: \$10–15M); some exploratory R&D is being funded by EE PV (estimated \$400K). Some basic research support by NSF and USDA is complementary. Federal R&D expenditures must be at a sufficient level to fund critical-mass groups to address fundamental problems in key areas, and the support must be consistent over the next 20–30 years to ensure successful R&D efforts. Suggested levels are a minimum of \$50M/year for improvements that will help reduce carbon emissions; substantially higher levels will be required to reap benefits that are outside of the scope of a budget driven by carbon reductions. Also, additional funds will be required for applied and production research for technology thrusts that prove worthy of commercialization; given the fundamental nature of the current research, it is not possible at this time to estimate what those requirements might be. <p>Market</p> <ul style="list-style-type: none"> Photoconversion processes have the potential to replace all fossil sources for power, fuel, materials, and chemicals production. <p>Nonenergy Benefits and Costs</p> <ul style="list-style-type: none"> Many spin-off technologies are possible. These include opto-electronics, biosensors, biocomputers, bioelectronics, and nano-scale devices. 	
Risk Factors	
<p>Technical Risk</p> <p style="text-align: center;">1 2 3 4 5 6 ⑦ 8 9 10</p> <p>Low High</p> <ul style="list-style-type: none"> Most photoconversion research is high risk, high payoff. <p>Commercial Risk</p> <p style="text-align: center;">1 2 3 4 5 ⑥ 7 8 9 10</p> <p>Low High</p> <ul style="list-style-type: none"> Initial commercial success in the biological area and solar cell supports the prospects for high payoff of this direction of R&D. <p>Ecological Risk</p> <p style="text-align: center;">1 2 ③ 4 5 6 7 8 9 10</p> <p>Low High</p> <ul style="list-style-type: none"> While technologies are still in the early stages of development, ecological risk should be low. 	<p>Human Health Risk</p> <p style="text-align: center;">1 2 ③ 4 5 6 7 8 9 10</p> <p>Low High</p> <ul style="list-style-type: none"> While technologies are still in the early stages of development, human health risk should be low. <p>Economic Risk</p> <p style="text-align: center;">1 2 3 4 5 ⑥ 7 8 9 10</p> <p>Low High</p> <ul style="list-style-type: none"> Economic risk will decrease with time and research investment. <p>Regulatory Risk</p> <p style="text-align: center;">1 2 3 4 5 6 7 8 9 10</p> <p>Low High</p> <ul style="list-style-type: none"> Not applicable. Lower than for current fossil technologies.
Key Federal Actions	
<ul style="list-style-type: none"> Federal R&D support enhances the scientific and technology base at the fundamental level where risk is too great for private sector support. The critical factor for success is critical-mass support for a sufficient period of time to develop key understanding and technology without large fluctuations in research funding. 	

Carbon Sequestration Technologies

9. Carbon Sequestration and Management

- 9.1 Augmented Ocean Fertilization to Promote Additional CO₂ Sequestration**
- 9.2 Advanced Chemical and Biological Conversion and Sequestration**
- 9.3 Terrestrial Storage of CO₂**
- 9.4 Carbon Sequestration in Soils**
- 9.5 Elemental Carbon Sequestration**
- 9.6 Ocean Storage**

9.1 AUGMENTED OCEAN FERTILIZATION TO PROMOTE ADDITIONAL CO₂ SEQUESTRATION

Technology Description
<p>CO₂ can be continually sequestered in the ocean in a variety of ways, one of the most important of which is the deposit on the ocean floor of the carbon-containing skeletal remains of plankton and diatoms. When carbon is thus removed from solution, it is replaced ultimately by CO₂ drawn from the atmosphere. Yet the vast majority of ocean area is photosynthetically barren, with littoral areas and parts of the Southern Ocean being the most productive. In these photosynthetically barren areas, usually only one nutrient is missing, commonly iron or nitrogen; the supply of this nutrient causes planktonic growth, and with this growth, the basic building blocks of the food chain are present, enabling carbon deposition on the ocean floor and CO₂ drawdown.</p> <p>The proposal would be to conduct experiments in enriching nutrient-poor sections of the ocean with either iron or nitrogen as a first step to understanding more about the potential to sequester CO₂ safely on the ocean floor through stimulation of growth of phytoplankton.</p> <p>System Concepts/Representative Technologies</p> <ul style="list-style-type: none"> • Iron enrichment experiments have delivered iron sulfate in liquid form from vessels. • For nitrogen enrichment, proposals have been made to use piped ammonia to provide nitrogen to nitrogen-poor ocean areas. <p>Technology Status/Applications</p> <ul style="list-style-type: none"> • Detailed experiments on iron fertilization have been conducted and reported in the scientific press. No such work has been done to date for nitrogen fertilization, but a pilot experiment to sequester 2 million tons of CO₂ annually has been proposed. Significant R&D will be required.
Current Research, Development, and Demonstration
<p>RD&D Goals</p> <ul style="list-style-type: none"> • Develop a clear understanding of technical issues: <ul style="list-style-type: none"> — What is the ultimate removal rate of the detritus of phytoplankton and their grazers to the ocean floor for different amounts of fertilization? — To what extent will increased phytoplankton lead to increases in the amount of larger fauna (e.g., fish), and if this leads to a greater harvest, to what extent can/should this be accounted for in atmospheric CO₂ reduction? • Adequate first order cost estimates per ton of CO₂ sequestered must be developed: one side of the equation would be the amount of CO₂ ultimately removed from the atmosphere per unit of fertilizer. Energy used in making and delivering the fertilizer must be taken into account in this calculation. • Experimentation will be required to determine the proper depth at which to supply nitrogen. Too shallow a depth will cause loss of some fertilizer to the atmosphere; too great a depth will make the fertilizer unavailable to phytoplankton. <p>RD&D Challenges</p> <ul style="list-style-type: none"> • Understanding the entire cycle of growth and decay that will be stimulated by fertilization. Environmental effects will be crucial: there is concern that too much fertilization could cause some ocean layers to become anoxic as long as the experiment continues, if too much fertilization occurs in a given area. • The ultimate goal is to find a fertilization rate that is both cost effective (and perhaps beneficial in producing more biomass) and without significant adverse environmental impact. <p>RD&D Activities</p> <ul style="list-style-type: none"> • To date, FE has not undertaken any experiments directly. • The International Energy Agency (IEA), partly supported by DOE-FE, has begun a program to research the effects of both types of fertilization. • Some research on ocean fertilization is also being done by the MARICULT program, a European collaborative on marine cultivation.
Commercialization and Deployment
<ul style="list-style-type: none"> • An international treaty will be needed to precede deployment.
Potential Benefits and Costs
<p>Carbon Reductions</p> <ul style="list-style-type: none"> • Theoretical potential is very large; work needs to be done to define maximum rates of fertilization that will have no significant adverse effects. Iron fertilization, which for practical purposes must occur in the Southern Ocean, has a maximum theoretical sequestration effect of 1–2 Gt C/year, but a realistic maximum of far less. <p>RD&D Expenditures</p> <ul style="list-style-type: none"> • FE has not yet proposed funding for RD&D for either type of fertilization. The IEA, partly supported by FE, has begun a program to research the effects of both types of fertilization. Some research on ocean fertilization is also being done by the MARICULT program. • It is suggested that research on this technology be part of a newly established carbon sequestration program. It is estimated that an annual federal budget on the order of \$125M through 2010, \$150M through 2020, and \$200M through 2030 is needed for this program. <p>Nonenergy Benefits and Costs</p> <ul style="list-style-type: none"> • Potential for significant increase in fisheries and other marine flora and fauna (see above).

Risk Factors

Technical Risk

1 2 3 4 5 ⑥ 7 8 9 10

Low High

- Probably the largest technical risk is that of anoxia, oxygen depletion of certain levels of the ocean. Thus a primary goal of research would be to find out locations and levels of fertilization that would carry no risk of this potential effect.
- To understand costs per ton of CO₂ sequestered, we must know the efficiency per unit of fertilizer. If it takes four times as much nitrogen or iron as thought to sequester one unit of CO₂, the cost per unit will be about four times as high: this kind of calculation is needed to separate economical projects from uneconomical ones.
- Nitrogen will have to be supplied at the proper depth(s), and some experimentation will be required to find these depth(s). Too deep, and it will be unavailable to phytoplankton; too shallow, and some will be lost to the atmosphere.

Commercial Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- Marine environmental protection will probably require significant impact assessment.

Ecological Risk

1 2 3 4 5 6 ⑦ 8 9 10

Low High

- Risks associated with possible oxygen depletion affecting ecology

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- Largest risks probably associated with ammonia manufacture and transport for nitrogen fertilization, and with ocean travel, especially in the Southern Ocean.

Economic Risk

1 2 3 4 5 6 7 8 9 10

Low High

- Not applicable. Main risks are probably those associated with public relations (e.g., the perception that humanity would be manipulating the oceans to deal with a problem of its own making).

Regulatory Risk

1 2 3 4 5 6 ⑦ 8 9 10

Low High

- May require international regulatory agreements

Key Federal Actions

- Work together with IEA and other federal agencies currently sponsoring such work to determine proper role for added work to be done by DOE/OFE.
 - In conjunction with above, do preliminary work to understand more about how efficiently nitrogen fertilization would work before undertaking a large-scale pilot project that would likely cost at least \$50 M.
 - In conjunction with bullet No. 1, do preliminary work to track how iron sulfate would disperse in Southern Ocean before starting larger-scale, longer-term project that would look at multi-year effects, with fertilization levels high enough to produce significant sequestration, but below levels that models would predict might begin to cause anoxia.
- Generally, before determining added key federal actions, it would be important to interface with other actors to maximize coordination.

9.2 ADVANCED CHEMICAL AND BIOLOGICAL CONVERSION AND SEQUESTRATION

Technology Description

Advanced chemical and biological sequestration and processing is aimed at permanent stable sequestration and recycling of carbon into new fuels and chemical feedstocks. Emissions are reduced through converting CO₂ into an environmentally benign product to reduce atmospheric CO₂ while generating liquid fuels, generating hydrogen as a fuel from coal without CO₂ emissions, and converting CO₂ into organic compounds. The major advantage of these technologies is that they eliminate hazards to humans and the environment that are intrinsic in the disposal of gaseous CO₂. Carbonate disposal does so by forming environmentally benign and thermodynamically stable waste forms; the other approaches instead generate viable products.

System Concepts

- The technology comprises four major areas: chemical sequestration as mineral carbonate, direct solar reduction of CO₂, conversion of coal to H₂ and methanol, and microalgae sequestration. Chemical sequestration takes advantage of the reaction of CO₂ with most magnesium- and calcium-bearing minerals to form solid carbonates. Direct solar reduction of CO₂ is aimed at producing liquid fuels from atmospheric CO₂ by using solar energy to break the CO₂ bond, allowing incorporation of the CO produced into standard fuel synthesis processes. The conversion of coal to H₂ and methanol is accomplished by mineralizing CO₂ during its reaction with steam to produce H₂ and reducing the captured CO₂ to methanol by direct solar reduction. Microalgae sequestration involves passing CO₂ through bubbling stacks, resulting in incorporation of CO₂ to organic carbon.

Representative Technologies

- Chemical sequestration as mineral carbonate
- Direct solar conversion of CO₂ to methanol
- Advanced conversion of coal to H₂
- Microalgae sequestration

Technology Status/Applications

- Chemical sequestration as mineral carbonate: Simple cost estimates for this technology (compared with existing industrial and mining processes) suggest that \$15/ton of CO₂ or \$55/ton of carbon **for conversion and disposal** is a reasonable cost goal to set. For comparison, at a coal-fired electric power plant with 45% conversion efficiency, complete CO₂ disposal at this cost would add \$0.011 to the cost of a kilowatt hour–electric. Further research is required; however, with a reasonable level of support, commercial implementation of the process could start before 2010.
- Direct solar conversion: The process has very promising economics since it produces a useful product. It is estimated that each square meter of mirror involved in the process would produce 3 GJ of fixed energy (44.4 gal of methanol) per year. At this level, methanol production from atmospheric CO₂ could be amenable to very rapid growth through mass production and subsequent operation by small businesses. Between now and 2010, this process will reverse very little CO₂; by 2020, it might fix one megaton of carbon per year. In its mature state, about 50 megatons to one gigaton of carbon might be fixed per year.
- Advanced conversion of coal to H₂: This process is promising because its products are high in value. For each ton of coal consumed, it avoids the emission of ½ ton of carbon and produces instead 440 gal of methanol while using 94 MBtu of solar energy at a cost of \$1.25/MBtu.
- Microalgae sequestration: This technology presents a possible low-cost option for sequestration. So far, it has resulted in a maximum carbon fixation of 100g/m³/day with 96% conversion efficiency of CO₂ to organic carbon. The cost is estimated at \$20/ton of CO₂ (\$73/ton of carbon).

Current Research, Development, and Demonstration

RD&D Goals

- Chemical sequestration as mineral carbonate: The basic principles have been demonstrated. Raw materials exist in vast quantities, and the thermodynamics have been worked out and are favorable, starting from common minerals. The chemistry has been demonstrated but still needs to be optimized. The total cost of R&D for this technology is estimated to be \$3 M/year for 5 years until a pilot plant is built.
- Direct solar conversion: The process is in the research phase. The spectrum of hot CO₂ has only recently been measured. The rates of all of the subsequent reactions are in the literature, but it is necessary to build integral demonstration units to see that all parts of the process play together as expected and to develop a data base for designs. The most basic parts of the R&D have been completed at a cost of \$600K. The chemical kinetics proof of principle will cost another \$800K. The integrated experiment with laser mock-up will cost \$1.5M.
- Advanced conversion of coal to H₂: The concept is in the research stage. It is clear that the CaO has to be developed to allow quicklime to undergo an indefinite number of cycles without caking. Additionally, the reaction of direct solar reduction of CO₂ needs further investigation. The most basic part of the R&D has been completed at a cost of ~600 K. The chemical kinetics proof of principle will cost another \$800K. The integrated experiment with laser mock-up will cost \$1.5M. The solar demonstration at the 10⁵ L/year level will cost \$5.5M; the first full 50 million L/year plant module will cost \$100M.
- Microalgae sequestration: The technology is in the developmental stage. Initial tests have been positive and merit further review.

Applications and target markets

- Chemical sequestration as mineral carbonate is applicable to the disposal of CO₂ from such large, concentrated, stationary point sources as electric power plants.
- Direct solar conversion is aimed at producing liquid fuels from effluent or atmospheric CO₂ by using solar energy.
- The H₂ produced during advanced conversion of coal to H₂ could be piped short distances to existing power stations for conversion to electricity either by combustion or fuel cell conversion.
- Microalgae sequestration has applications with ongoing biomass programs and co-firing efforts in utilities.

RD&D Challenges

- Chemical sequestration as mineral carbonate: Research will be required in a broad number of areas from mineral exploration and mining engineering to research in the fairly complex carbonation chemistry of magnesium and calcium silicates. In addition, further development is needed of the chemistry of extracting magnesium from mineral ores and of chemical processes in chemical engineering research.

Current Research, Development, and Demonstration (continued)

RD&D Challenges (continued)

- Direct solar conversion: The spectrum of hot CO₂ has only recently been measured. It is necessary to build integral demonstration units to see that all parts of the process play together as expected and to develop a data base for designs. Basic research is needed in CO₂ and CO, high-temperature materials, ceramics and metals, advanced combustion, and fluid dynamics and modeling.
- Advanced conversion of coal to H₂: Technology needs include research into the basic nature of the reaction between coal, steam, and quicklime; basic properties, including theoretical understanding of CO₂ and CO; and basic research in high-temperature materials, ceramics and metals, advanced combustion, and fluid dynamics and modeling.
- Microalgae sequestration: R&D is needed in genetic engineering to improve plant uptake and in various feedstream properties to determine the robustness of plants.

RD&D Activities

- Programs in mineral fixation, solar-thermal production of methanol, and coal-based production of H₂ and methanol are under way at LANL. A program in microalgae supported by EPRI is active at the University of Miami.

Potential Benefits and Costs

Carbon Reductions

Carbon reductions from this pathway are not likely to occur without policy changes, and such changes are not considered in this study.

- Chemical sequestration as a mineral carbonate: 100% efficacy at \$15/ton for CO₂. (@60% power plant (IGCC) efficiency—395 MtC/year at 300 GW)
- Direct solar reduction of CO₂: 60% efficacy assuming recycling at \$7/ton for CO₂ with credits for methanol. (@60% power plant (IGCC) efficiency—236 MtC/year at 300 GW)
- Advanced conversion of coal to H₂: [60 to 80]% efficacy at \$7/ton for CO₂. (@60% power plant (IGCC) efficiency—270 MtC/year at 300 GW—70% efficacy of process)
- Microalgae sequestration: 100% efficacy at \$20/ton for CO₂
- (@60% power plant (IGCC) efficiency—395 MtC/year at 300 GW)

RD&D Expenditures

- It is suggested that research on this technology be part of a newly established carbon sequestration program. It is estimated that an annual federal budget on the order of \$125M through 2010, \$150M through 2020, and \$200M through 2030 is needed for this program.

Market

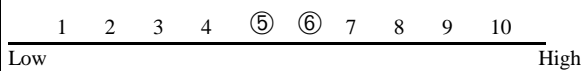
- The versatility of the technologies could allow them to capture a large fraction of the CO₂ mitigation market if CO₂ credits were implemented.

Nonenergy Benefits and Costs

- These technologies are largely environmentally benign and result in no hazardous byproducts. They also produce commercially viable products that may be used by industry. Finally, the versatility of these technologies will crosscut several major areas of concern relating to CO₂ management.

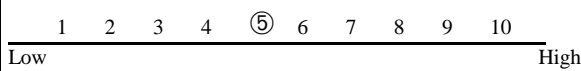
Risk Factors

Technical Risk



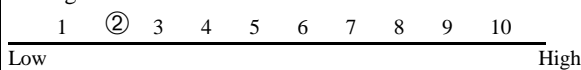
- These technologies are novel approaches.

Commercial Risk



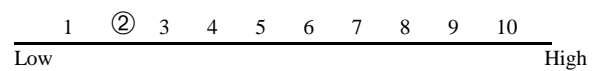
- The technologies are still too young to fully evaluate the commercial risk.

Ecological Risk



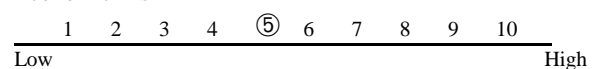
- No hazardous byproducts are associated with these technologies.

Human Health Risk



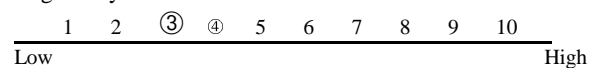
- The risks involved are limited to the individual processes themselves.

Economic Risk



- These technologies are still too young to fully evaluate the economic risk.

Regulatory Risk



- The regulatory processes are driven at a large scale and by mining; however, this is true of any large-scale comprehensive method.

Key Federal Actions

- Government/industry partnerships are recommended.
- The establishment of a long-term sequestration R&D program is recommended.

9.3 TERRESTRIAL STORAGE OF CO₂

Technology Description
<p>Terrestrial storage of CO₂ involves capturing CO₂ and injecting it into subsurface repositories such as deep coalbeds, depleted oil and gas reservoirs, and deep, confined saline aquifers. The technology for subsurface injection is readily adaptable from the petroleum industry for application to CO₂ sequestering. These technologies include the drilling and completion of injection wells, compression and long-distance transport of gases, subsurface reservoir characterization, multi-component reservoir simulation, and experience with the operational issues of CO₂ injection for enhanced oil recovery. Terrestrial storage in geologic repositories will reduce GHG emissions by long-term sequestration from the atmosphere. The injection of CO₂ into depleted oil and gas reservoirs and deep coalbeds has the potential for storing CO₂ and yielding commercially valuable hydrocarbons.</p> <p>System Concepts</p> <ul style="list-style-type: none"> • CO₂ is captured, processed, compressed, and transported by pipeline to a geologic structure having sufficient reservoir porosity and permeability for commercial utility. • Storage may entail geochemical reactions that tend to form carbonates in silicic host rock, enhancing containment. <p>Representative Technologies</p> <ul style="list-style-type: none"> • Technologies will borrow extensively from the petroleum industry in areas of drilling, stimulation, and completion of injection wells; processing, compression, and pipeline transport of gases; operational experience of CO₂ injection for enhanced oil recovery; subsurface reservoir engineering and characterization including multi-component reservoir simulation; and natural gas storage in saline aquifers. <p>Technology Status/Applications</p> <ul style="list-style-type: none"> • The petroleum technology is readily adaptable to subsurface CO₂ storage. • Natural gas is routinely transported and stored in subsurface reservoirs and aquifers. • Reservoir storage and containment parameters have yet to be defined. • Economic feasibility, capital and operating costs for the construction of a CO₂ collection and transport infrastructure at varying distances from a stationary sources have yet to be determined.
Current Research, Development, and Demonstration
<p>RD&D Goals</p> <ul style="list-style-type: none"> • Conduct geologic and reservoir engineering studies to define required storage integrity, flow properties, and volume capacity of geologic repositories. • Estimate the costs of infrastructure development for terrestrial CO₂ disposal. • Conduct fate and transport modeling studies, including geochemical reactions with formation fluids and rocks. • Quantify the safety and environmental requirements of a storage repository. • Demonstrate the commercial feasibility of the technology with a field test. <p>RD&D Challenges</p> <ul style="list-style-type: none"> • Identify sufficient CO₂ storage capacity in economical proximity to large, stationary sources. • Establish reservoir criteria for storage integrity, quantify storage capacity, and evaluate environmental acceptability. • Modify existing reservoir simulation codes to included CO₂/carbonate geochemistry for long-term fate and transport studies. <p>RD&D Activities</p> <ul style="list-style-type: none"> • DOE/FE has initiated a study of the economic, legal, environmental, and social issues use of the Mt. Simon aquifer underlying portions of the U.S. Midwest. • Commercial recovery of coalbed methane by CO₂ injection has been demonstrated by industry. • FETC has identified promising sites for CO₂ sequestration in Texas where large power plants are close to high-capacity depleted oil and gas reservoirs.
Recent Success
<ul style="list-style-type: none"> • Statoil has a project to store 1 million tonnes per year of CO₂ from the Sleipner Vest gas field in a sandstone aquifer 1000 m beneath the North Sea. • Dakota Gasification Company recently signed a contract to transport 2 million tonnes of CO₂ per year captured from the gasification of lignite to PanCanadian Petroleum for enhanced oil recovery in Canada. • Industry has demonstrated injection of CO₂ into coalbeds for enhanced methane production.
Commercialization and Deployment
<ul style="list-style-type: none"> • About 70 oil fields worldwide use CO₂ for enhanced oil recovery. • No commercial aquifer storage sites for CO₂ are operating in the United States. • There is commercial and industrial experience with over 400 wells for injecting industrial waste into deep aquifers. • The Mt. Simon aquifer underlying Illinois, Indiana, Michigan, Kentucky, and Pennsylvania has been approved for industrial waste disposal and underlies a region with numerous fossil energy power plants. • Injection of CO₂ into depleted oil and gas reservoirs and deep coalbeds can provide incremental hydrocarbon recovery.

Potential Benefits and Costs

Carbon Reductions

- It might be feasible to inject a large fraction of the CO₂ produced from U.S. power plants on site without a long-distance pipeline transportation infrastructure.

RD&D Expenditures

- It is suggested that research on this technology be part of a newly established carbon sequestration program. It is estimated that an annual federal budget on the order of \$125M through 2010, \$150M through 2020, and \$200M through 2030 is needed for this program.

Nonenergy Benefits and Costs

- Injecting CO₂ into oil fields could recover incremental oil, boosting U.S. production and reducing oil imports.
- Successful implementation would create domestic and international market opportunities for U.S. companies for site-specific studies and project implementation.

Expected Cost Per Ton of Carbon Sequestered

- The cost of injecting CO₂ into depleted oil and gas reservoirs is typically less than \$10/ton. Costs have been estimated to range from \$2 to \$8/ton of CO₂ for aquifer storage, excluding power plant modifications. The cost of injecting CO₂ into depleted oil and gas reservoirs is less than \$10/ton. Costs have been estimated at \$5 to 15/ton of CO₂, equivalent to \$18 to \$55/ton of carbon. Assuming a 1% per year reduction in total system costs, the cost per ton of carbon can be reduced to \$17 to \$52 by 2000 and to \$16 to \$47 by 2010. Assuming an accelerated RD&D program goal of a 3% per year reduction in total system costs, the costs can be reduced to \$16 to \$47 by 2000 and \$11.61 to \$34.82 by 2010.

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- The technology for subsurface injection of CO₂ can be readily adapted from the petroleum industry. Site-specific long-term fate and transport studies are required to demonstrate successfully sequestration.

Commercial Risk

1 2 3 4 5 ⑥ 7 8 9 10

Low High

- Individual components of petroleum technology have yet to be integrated and a pilot field test successfully completed for commercial acceptance. The potential domestic and international market for CO₂ sequestration services is very large and intimately related to the use of fossil fuels, the implementation of carbon taxation, and regulatory and governmental activities. A significant infrastructure investment for the collection, transportation, and disposal of CO₂ would be required.

Ecological Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Ecological risk is primarily associated with the collection and transportation infrastructure. CO₂ storage in a geologically stable repository presents minimal risk to the biosphere. Land subsidence of uplift over time is a possibility. R&D needed to find out if there is a possible subsurface ecology risk.

Human Health Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- CO₂ is present in low concentrations in the atmosphere. Human health risk is primarily associated with industrial accidents in the collection and transportation of CO₂.

Economic Risk

1 2 3 4 5 6 7 8 9 10

Low High

- Not applicable. Economic feasibility has yet to be evaluated or demonstrated. A field pilot test with an industrial partner is needed to establish capital and operating costs and operational parameters. The rate of return on capital invested for infrastructure is unknown.

Regulatory Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- Regulatory requirements are likely to be similar to those for the natural gas transportation and storage industries.

Key Federal Actions

- Survey data collected by federal and state agencies and industry on the distribution, formation, and potential storage capacity of depleted oil and gas reservoirs, deep coalbeds, and saline aquifers suitable for CO₂ sequestration.
- Demonstrate technical and economic feasibility and perform environmental assessment to attract commercial interest and support for using captured CO₂ for long-term sequestration.
- Conduct field demonstration projects of CO₂ storage in different types of geologic repositories.

9.4 CARBON SEQUESTRATION IN SOILS

Technology Description

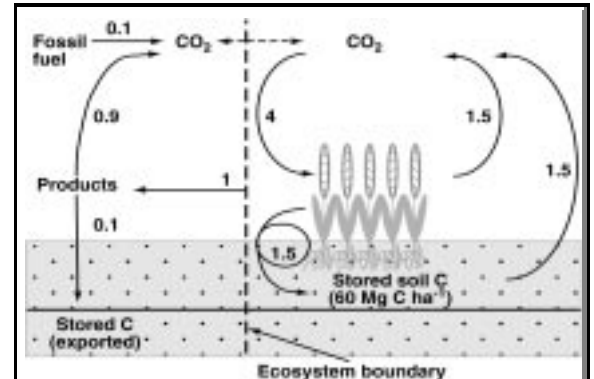
The IPCC (Second Assessment Report, 1995 Chapter 23, Working Group II) estimates that between 400 and 800 Mt C/year could be sequestered in agricultural soils worldwide by implementation of appropriate management practices that also increase agricultural productivity. These practices include increased use of crop residues, reduced tillage and restoration of wasteland soils. Overall, however, the capacity of soils to store carbon is finite and, if best practices are employed worldwide, can lead to a new equilibrium soil organic matter (SOM) content in from 50 to 100 years.

System Concepts

- When grasslands are broken for agricultural use, SOM in the densely rooted upper half-meter or so of soil is exposed to oxidation with consequent emission of CO₂ to the atmosphere.
- When wetlands are drained, their highly organic soils are aerated and exposed to oxidation with consequent CO₂ emissions into the atmosphere. Further, the dry surfaces of drained organic soils are exposed to wind erosion, and the dispersed organic particles are quickly oxidized.
- The net effects on SOM of forest land conversions to agriculture are more difficult to estimate and depend on the mineral composition, aeration, and acidity of the original soils. They depend, too, on climate and on the crop or pasture vegetation that replaces the forest. Even though a net gain in SOM is possible in some cases, maintenance of current forests and reforestation offer much greater opportunity for carbon sequestration.

Representative Technologies

- Minimum tillage, now practiced on more than 30% of U.S. farmlands, leads to increases in SOM.
- Increased return of crop residues to the soil provides a source of organic matter, some of which remains in the soil and increases carbon sequestration.
- Irrigation and appropriate use of fertilizers increases crop and root biomass, thereby increasing SOM.
- Return of agricultural lands to forests and grasslands initiates recovery of SOM content, and revegetation of degraded lands stabilizes them against further erosion and increases carbon storage in the soil.
- Plant breeding and genetics to increase belowground storage.



This diagram represents an agroecosystem (crop field) with the general direction and dimensions of CO₂ fluxes. Arrows allude to photosynthesis, plant and soil respiration, plant litter, and soil organic matter transformations. Carbon sequestering practices lead to an imbalance between carbon gains and losses and therefore to an increase in soil organic matter.

Current Research, Development, and Demonstration

RD&D Goals

- Development of minimum tillage and residue management practices that are both sustainable and profitable and adaptable to all climatic regions.
- Understanding the sensitivity of carbon-sequestration techniques to climatic changes.
- Understanding the environmental, social, and economic consequences of large-scale biomass production on lands currently producing food and feed crops.

RD&D Activities

- In 1995, USDA supported precision agriculture research at 15 locations for a total of \$4.4M. By 1996, 125 people were involved in precision agriculture research, and funding was \$26M—half for precision agriculture and half for supporting research. About \$9M was transferred to land-grant universities through the Cooperative State Research Education and Extension Service.
- Private investment in precision agriculture is growing. A University of Georgia home page on precision farming links lists more than 50 companies in Australia, Canada, France, Germany, Sweden, the United Kingdom, and the United States offering precision agriculture services. Companies involved in precision agriculture research include Case IH, John Deere, Leica, Lockheed Martin, Agrium, Farmland Industries, and Monsanto.

Recent Success

- Aboveground carbon storage is complemented by belowground carbon storage in soil organic matter and roots. Roots of trees, shrubs and herbaceous species can grow considerably deep into the soil profile thereby reducing the possible release of CO₂ into the atmosphere. A 1994 article in *Nature* reported that pasture grasses planted to increase beef production in the South American savannas may remove in a year as much as 2 Gt of CO₂ from the atmosphere. Carbon storage occurred as deep as a meter in the savanna soil.

Commercialization and Deployment

- The need for increased sequestration of carbon in soils will not, of itself, motivate farmers. The practices cited can be fostered with incentives in the form of subsidies keyed to amounts of carbon sequestered. More practical would be demonstrations that these practices increase farm profitability. Minimum tillage has already been shown to do so. In the developed world, improvements in irrigation and fertilization management can be effected through a range of satellite-based, computer-controlled techniques known as “precision farming.” More traditional extension methods may be needed, for now, in the developing countries, although with the development of appropriate institutions, high-tech solutions may be deployable there, too.

Potential Benefits and Costs

Carbon Reductions

- The carbon loss from cultivated soils has been estimated at 55 Gt worldwide. The current carbon stock in cultivated soils is 167 Gt to a depth of 1 m. Calculations have been made that 40 GtC can be stored in soil over a 50 to 100 year period (linear rates of 400 to 800 MtC/year).

RD&D Expenditures.

- It is suggested that research on this technology be part of a newly established carbon sequestration program. It is estimated that an annual federal budget on the order of \$125M through 2010, \$150M through 2020, and \$200M through 2030 is needed for this program.

Market

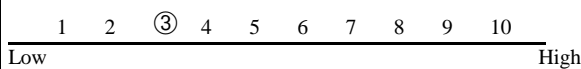
- At present, there is no market value for carbon in soils. Recognition of such a market would encourage land managers to apply techniques leading to carbon storage (e.g., precision farming, minimum tillage, deep rooted crops, agro-forestry, riparian areas).

Nonenergy Benefits and Costs

- Within range, an increase in soil organic matter leads to improvements in soil tilth, reduction of soil erosion, and improvements in crop nutrition.

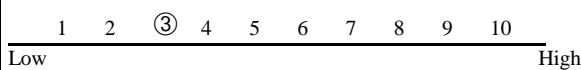
Risk Factors

Technical Risk



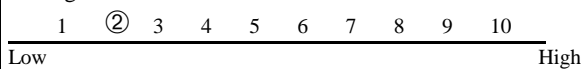
- Obtaining accurate national and regional carbon accounting.

Commercial Risk



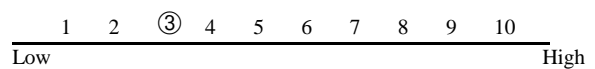
- Market value of carbon sequestration activities.

Ecological Risk



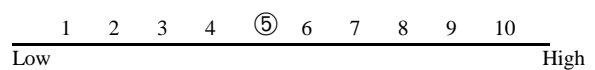
- Carbon sequestering activities should lead to ecological enhancement.

Human Health Risk



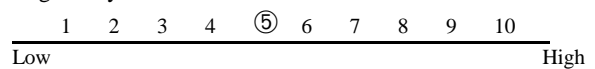
- Public perception of genetically-altered organisms

Economic Risk



-

Regulatory Risk



- Public opposition to precision farming and gene manipulation.

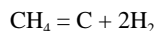
Key Federal Actions

- Maintain existing research infrastructure (USDA/Forest Service, ARS, NRCS).
- Provide incentives for farmer adoption of carbon sequestration practices and other resource conserving practices.
- Include carbon sequestration as another goal of land use planning/land management.

9.5 ELEMENTAL CARBON SEQUESTRATION

Technology Description

The production of hydrogen by the thermal decomposition of natural gas, followed by sequestration or sale of the particulate carbon formed, is an alternative to the conventional method in which steam reforming of natural gas is followed by a water/gas shift and separation and sequestration of CO₂.



System Concepts

- The production of hydrogen from fossil and carbonaceous fuels, with reduced CO₂ emission to the atmosphere, is key to the production of hydrogen-rich fuels for mitigating the CO₂/GHG climate change problem. The basic reaction is the high-temperature thermal decomposition of natural gas to elemental carbon and gaseous hydrogen.
- The reasons for setting forth this technology as the basis for a CO₂ mitigation process are as follows:
 - It would provide a zero-CO₂-emissions process for producing hydrogen.
 - The process energy required to produce a mole of hydrogen would be lower than for any other production method, including steam reforming of methane.
 - It would be a one-step reaction process with separation of hydrogen from carbon.
 - The resulting carbon solid could be relatively easily separated from the gas stream.
 - The carbon could be more readily disposed of than CO₂. It would be a relatively stable and storable solid that could be landfilled, stored in mines, or sunk to the ocean floor. Carbon sequestration may be more acceptable than CO₂ sequestration.
 - The carbon would be pure and could be marketed as a commodity. Millions of tons of carbon are used yearly as a strengthening agent in rubber tires and as pigments in paints, printing inks, and facsimile machines. It is also possible to use carbon as a soil additive. Another possibility is to use carbon as a construction material in civil works, highways, and housing. Just as ash from coal is a useful product, carbon from methane could be considered the ash of natural gas with respect to the greenhouse problem.
 - The projected cost of production of hydrogen from methane decomposition is competitive with the cost of steam reforming of methane. If the carbon produced could be sold as a commodity, the net cost of this process would be much lower than the cost of steam reforming of hydrogen.
 - The hydrogen could be used efficiently in fuel cells or reacted with CO₂ to produce methanol, which would fit well into the current liquid fuel infrastructure.
- The main negative aspect of this technology is that only a little more than half the energy from the natural gas resource would be extracted in the form of hydrogen. However, this ratio is not much worse than for other CO₂ sequestration technologies. Furthermore, the carbon energy, is not destroyed. It may be possible to use it at a later date when atmospheric CO₂ is less problematic.

System Components

- Thermal decomposition reactor
- Carbon separation and utilization

Representative Technologies

- High-temperature reactors
- Molten metal reactors
- Particulate removal from the gas stream

Technology Status/Applications

- Thermal decomposition of methane to produce carbon black has been practiced for years in the thermal black process. Hydrogen has been produced from methane decomposition on a demonstration scale in a catalyzed fluidized bed. The plasma decomposition of methane has been performed on a pilot plant scale. However, these are relatively inefficient processes with efficiencies of only about 50% because they have not been specifically geared to hydrogen production.

Current Research, Development, and Demonstration

RD&D Goals

- To use methane decomposition as a CO₂ mitigation technology, it is necessary to develop an efficient reactor that would produce hydrogen continuously at a thermal efficiency of >70%. Several reactor types have been proposed, including a molten metal reactor. Study is required to investigate the autocatalytic effect of the carbon formed on the kinetics of the methane decomposition reactor as it affects reactor design.
- The possibilities for using large amounts of carbon as a material commodity should be investigated. It could become a new construction material or a soil enhancer for farming. The lifetime stability of terrestrially sequestered carbon needs clarification.

Applications and Target Markets

- This technology is geared toward marketing decarbonized fuels, hydrogen and methanol. The methanol could be produced from the reaction of hydrogen with CO₂ from a coal-fired power plant. The methanol would then be used in either internal combustion or fuel cell vehicles. Thus the carbon would be used twice—once to generate electrical power and a second time to power transportation.
- The carbon would be directed toward material commodity markets—tires, pigments, and construction materials.

RD&D Challenges

- Develop a continuous high-thermal-efficiency thermal decomposition reactor for methane.
- Develop efficient separation systems for separating solid carbon from a gaseous hydrogen stream.
- Determine the applications of solid carbon as a materials commodity and the stability of carbon in a sequestered condition.

RD&D Activities

- A small conceptual research program funded by DOE has been performed at BNL for \$50K. Kvaerner Company in Norway has worked on the plasma decomposition of methane but not on the thermal degeneration. The old thermal black process has not been developed further.

Commercialization and Deployment

Potential Benefits and Costs

Carbon Reductions

- Thermal decomposition of natural gas, storing or using the carbon as a material, and using the hydrogen as such or converting it to methanol for use in fuel cells for transportation could reduce carbon emissions by 80% compared with using gasoline derived from petroleum to power vehicles. The cost per ton of CO₂ deleted from the atmosphere would be negligible because of the revenue from selling methanol or hydrogen as a fuel replacing gasoline to drive engines. The mass of carbon to be sequestered or marketed would be on the order of 400 million tons, which is less than 25% of the mass of CO₂ emissions from coal and oil currently consumed in the United States. (See the Systems Concepts section for further discussion of benefits.)

RD&D Expenditures

- It is suggested that research on this technology be part of a newly established carbon sequestration program. It is estimated that an annual federal budget on the order of \$125M through 2010, \$150M through 2020, and \$200M through 2030 is needed for this program.

Market

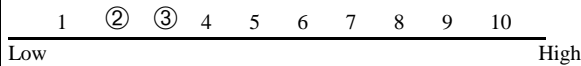
- This technology is a basic global technology applied to on a prime large fuel resource for removal of carbon (i.e., natural gas). It would produce a prime carbon-free fuel, hydrogen, that could be used as a basic fuel in all engines and conversion devices. It would supply the hydrogen economy without producing and emitting CO₂.

Nonenergy Benefits and Costs

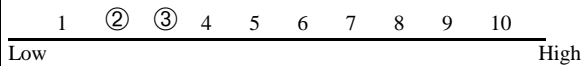
- This technology produces carbon as a materials commodity for construction and the infrastructure. It produces hydrogen to be used for fuel and for chemical and fertilizer production.

Risk Factors

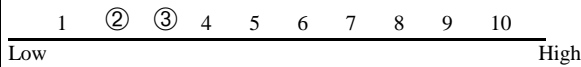
Technical Risk



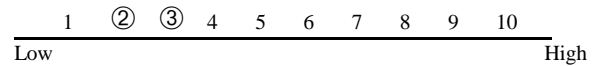
Commercial Risk



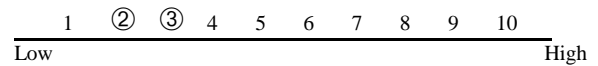
Ecological Risk



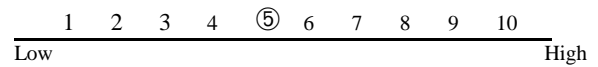
Human Health Risk



Economic Risk



Regulatory Risk



Key Federal Actions

- A 10-year effort cofunded by government and industry is recommended to reach commercial goals.

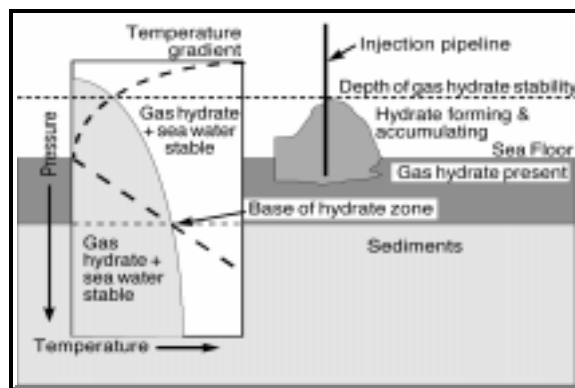
9.6 OCEAN STORAGE

Technology Description

Gas hydrates are nonstoichiometric compounds in which the gas molecules are encaged within a host crystal lattice of water molecules (46 H₂O tetrahedral coordinated water molecules and eight cavities for CO₂ and CH₄) with an ideal composition of 8M:46H₂O (i.e., n=5.75). The water molecules that do not react chemically with the encaged molecules can form CO₂/CH₄ mixtures. CO₂ could be pumped into regions such as deep oceans where hydrate is stable and sequestered as accumulated gas hydrate. The drawing is a conceptual cross-section of CO₂ introduced to deep seafloor or within seafloor sediments. (The diagram shows stability field of gas hydrate relative to hydrothermal and geothermal pressure and temperature gradients in the ocean and seafloor.)

System Concepts

- In arctic oceans, permafrost regions, and deep oceans, the pressure and temperature conditions favor gas hydrate stability. At deep ocean depths, CO₂ hydrates form below temperatures of 10°C. As a result of these same in situ processes, CH₄ hydrates form on the ocean floor and within ocean sediments. This CH₄ stabilized as hydrate is a major reservoir of GHGs. The sequestration process is the opposite of systems envisioned to extract CH₄ hydrates from the seafloor as an energy source. CO₂ could be piped into regions where hydrate is stable and sequestered as accumulated gas hydrate at the seafloor-ocean interface or within the accumulating sediments (the possible reservoir is basically unlimited because of the areal extent of ocean and permafrost regions where hydrates are stable). The advantages of the gas hydrate sequestration pathway are that hydrate formation results in a significant reduction in volume for equivalent mass and that the process may be less rate dependent than relying on CO₂ mixing with sea water.



Conceptual cross-section of CO₂ introduced to deep seafloor.

Representative Technologies

- Performance assessment
- Deep ocean engineering
- Deep ocean science
- Fate and transport geochemistry
- Three-dimensional characterization and monitoring

Technology Status/Applications

- This is a frontier technology. Japan, India, and the United States are investigating the somewhat reverse process of mining the seafloor or arctic gas hydrate for methane. Since this work is still developmental, costs are difficult to estimate. However, since the ambient pressure and temperature conditions at the seafloor form the gas hydrate, the basic cost is for the deep water pipelines to bring CO₂ as a gas or liquid to the appropriate location where the pressure and temperature conditions favor clathrate stability. Research suggests that ocean sequestration of CO₂ would cost from \$5 to \$50 per tonne of carbon depending on the site and other factors.

Current Research, Development, and Demonstration

RD&D Goals

- Understanding of CO₂ fate and transport in deep ocean waters and sediments.
- Comparative cost and risk evaluation among this and other technology pathways.

RD&D Challenges

- Performance assessment: engineering risk/decision analysis, total system environmental risks, and comparative cost and risk evaluation among this and other technology pathways.
- Deep ocean engineering: completion to targeted areas, size to handle volumes, durability, and cost-effectiveness.
- Deep ocean science: characterization of pressures and temperatures, deep ocean currents and transport, deep ocean sedimentation, and deep ocean ecosystems.
- Fate and transport geochemistry: geochemistry complex mineral and fluid interaction with CO₂-bearing phases, fate of clathrates at various temperature and depths (pressures) in the ocean, and modeling of temporal (over 100 years) and spatial behavior.
- Three-dimensional characterization and monitoring: volumes and suitability, location, areal extent, flow and availability, geostatistics.

Current Research, Development, and Demonstration (continued)

RD&D Activities

- RD&D activities for CO₂ sequestration as gas hydrates are not currently funded. Ongoing basic science programs, waste storage programs, and engineering development programs for fossil energy extraction may provide an existing foundation for the development of the gas hydrate sequestration pathway. Some of the basic science (e.g., deep ocean science, fate and transport geochemistry) can be leveraged by ongoing general R&D in these fields. In the broad sense, the level of activity for general research in these related fields is as follows:
 - deep ocean science sponsored by NSF (\$20M), NRL (\$100M), IPOD (\$5M), industry (\$10M), and foreign agencies (\$10M).
 - fate and transport (e.g., geochemistry and three-dimensional characterization and monitoring) sponsored by NSF (\$1M), NRL (\$1M), other government agencies (e.g., USGS) (\$1M), and foreign agencies (\$50M).
- The general components of the RD&D activities for deep ocean engineering and performance assessment technologies are being developed for fossil energy extraction and waste storage. The current levels of RD&D for fossil energy extraction and waste storage are as follows:
 - deep ocean engineering sponsored by NRL (\$50M), IPOD (\$5M), industry (\$10M), and foreign agencies (\$150M).
 - performance assessment sponsored by DOE (\$100M), NRC (\$10M), EPA (\$10M), industry (\$100M), and foreign agencies (\$100M).

Recent Success

Commercialization and Deployment

Potential Benefits and Costs

Carbon Reductions

- 100% efficacy (assuming no significant leakage during transport and total conversion to clathrate and mixing with deep waters) at \$0.20 to \$10/tonne of CO₂ (\$0.73 to \$37/tonne of carbon).

RD&D Expenditures

- It is suggested that research on this technology be part of a newly established carbon sequestration program. It is estimated that an annual federal budget on the order of \$125M through 2010, \$150M through 2020, and \$200M through 2030 is needed for this program.

Market

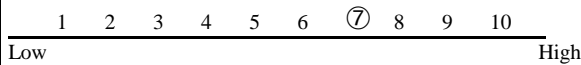
- The large potential reservoir, the reliance on natural processes (e.g., the enhanced stability field due to the deep ocean or permafrost region pressure and temperature conditions), and the areal distribution of deep oceans and arctic region represented in the gas hydrate sequestration pathway would allow this pathway to capture a large fraction of the CO₂ mitigation market if CO₂ credits are implemented.

Nonenergy Benefits and Costs

- These technologies are largely environmentally benign and may facilitate the production of ocean methane clathrates as an energy source. For example, the formation of CO₂ clathrates may reduce the subsidence related to methane extraction.

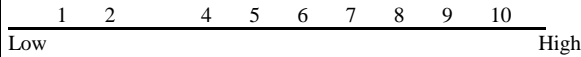
Risk Factors

Technical Risk



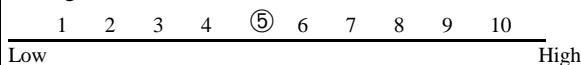
- These technologies are novel approaches.

Commercial Risk



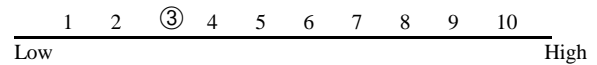
- The technologies are still too young to fully evaluate the commercial risk.

Ecological Risk



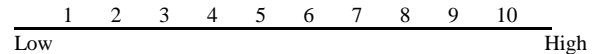
- No hazardous byproducts are associated with these technologies. However, the effects on methane release need to be evaluated through a total system performance assessment.

Human Health Risk



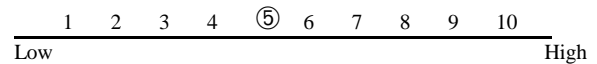
- The risks involved with these technologies are limited to the individual processes themselves.

Economic Risk



- These technologies are still too young to fully evaluate the economic risk.

Regulatory Risk



- The regulatory processes are driven at a large scale and by mining; however, this is true of any large-scale comprehensive method.

Key Federal Actions

- The establishment of a long-term sequestration R&D program and government/industry partnerships.

Crosscutting Technologies

10. Crosscutting

10.1 Fuel Cell Systems for Stationary and Transportation Applications

10.2 Hydrogen

10.3 Sensors and Controls

10.4 Transmission and Distribution Technologies

10.5 Power Electronics and Electric Machinery

10.6 Energy Storage

10.7 Modeling, Simulation, and Analysis

10.1 FUEL CELL SYSTEMS FOR STATIONARY AND TRANSPORTATION APPLICATIONS

Technology Description
<p>Fuel cells are devices that change chemical energy directly into electrical energy without any combustion. Operating on hydrogen, a fuel cell does not emit CO₂ and is projected to be up to two times as efficient as other advanced power generation technologies. A highly efficient end-use/conversion device such as a fuel cell is necessary to offset the energy penalty associated with producing hydrogen and achieve the full benefits of a transition to a hydrogen economy.</p> <p>System Concepts</p> <ul style="list-style-type: none"> • A fuel cell power plant typically consists of three main parts: <ul style="list-style-type: none"> — A fuel processor that converts a fuel (e.g., natural gas, diesel fuel, ethanol, methanol, gasoline) to a hydrogen-rich gas. Storage technologies to allow pure hydrogen to be carried aboard vehicles are being developed, as well as fuel cells that operate directly on methanol. — The fuel cell stack system that converts hydrogen into direct-current (dc) electricity. — A power conditioner that converts the dc electricity to regulated alternating-current (ac) electricity. • Along with electricity, fuel cells produce heat, which can be used directly or, if the temperature is high enough, as input to a bottoming cycle to produce additional electricity. <p>Representative Technologies</p> <ul style="list-style-type: none"> • Fuel cells are commonly classified according to the type of electrolyte employed. The United States is actively developing and demonstrating phosphoric acid, molten carbonate, solid oxide, and polymer electrolyte (also known as proton exchange membrane) fuel cells for power generation in stationary applications (including distributed and on-site power) and transportation applications. <p>Technology Status/Applications</p> <ul style="list-style-type: none"> • Large-area fuel cells producing up to several megawatts are being demonstrated by utilities; smaller systems producing up to 100 kW are being demonstrated for transportation and smaller industrial and residential applications. • About 100 phosphoric acid powerplants (200 kW) are in use with very high availability. • Molten carbonate and solid oxide fuel cells have been scaled up to commercial size cells and stack hardware. Integrated systems are being tested. • Polymer electrolyte fuel cells (10 to 30 kW) have been built and tested in buses and small vans. U.S. automakers have announced they will produce prototype mid-size sedans powered by fuel cells in the 2000–2001 time frame. Performance simulations indicate fuel economy of 80 mpg (gasoline equivalent) is achievable.
Current Research, Development, and Demonstration
<p>RD&D Goals</p> <ul style="list-style-type: none"> • Utility fuel cell power generation systems cost about \$3000 per installed kilowatt. The cost goal is \$1000/kW. Other goals are 50 to 70% energy efficiency (depending on the application), near zero regulated emissions, and a 40,000-hour lifetime. Smaller systems, based on the polymer electrolyte technology, are expected to enter the industrial, commercial, and residential markets at \$1000 to 1500/kW. • Costs for transportation systems are projected to be about \$300/kW (based on high-volume production of current fuel cell technology). Cost and performance goals for the year 2004 are as follows: \$50/kW (based on high-volume production), 48% energy efficiency, emissions levels much lower than federal Tier II standards, and a 5000-hour lifetime. <p>RD&D Challenges</p> <ul style="list-style-type: none"> • Reduction of costs through further development and optimization of fuel cell materials, designs, and systems for both stationary and transportation applications. • Development of small-scale reformers (including microtechnology-based components) that will enable the use of liquid transportation fuels. • Demonstration of compact, cost-effective, on-board hydrogen storage systems. • Demonstration of required durability in all applications. <p>RD&D Activities</p> <ul style="list-style-type: none"> • DOE's fuel cell programs are carried out by the private sector through cost-shared cooperative agreements and by the national laboratories. • DOT is developing fuel cell-powered transit buses, DOD is funding development efforts on fuel cells operating on jet and diesel fuel, and NASA fuel cell efforts are focused on aerospace applications. • EPRI and GRI are cooperating with the FE stationary fuel cell program. • Fuel cell technology is strongly supported abroad by both industry and government.
Recent Success
<ul style="list-style-type: none"> • Approximately one hundred 200-kW phosphoric acid fuel cell plants have been delivered. • Several polymer electrolyte fuel cell-powered buses and light-duty passenger vehicles are being tested.
Commercialization and Deployment
<ul style="list-style-type: none"> • Phosphoric acid fuel cell powerplants are at market-entry status (100 have been delivered) for small on-site systems of 200 kW. Plants now operating have achieved up to 20,000 hours of operation. The primary issue is to reduce costs from ~\$3000/kW to \$1500/kW. • Polymer electrolyte fuel cells are in the development phase for systems of up to about 100 kW. • Molten carbonate and solid oxide fuel cells are expected to be ready for commercial use by the year 2000. Energy Research corporation and M-C Power are the major U.S. suppliers of the molten carbonate technology. IHI, Mitsubishi, Toshiba, and Hitachi (Japan), and the European Direct Fuel Cell Consortium are also developing this technology.

Commercialization and Deployment (continued)

- Westinghouse is the major U.S. developer of the tubular solid oxide fuel cell; planar solid oxide technology is under development at Allied Signal, ZETEK, SOFCO, and TMI in the United States. The technology is also under development in Europe and Japan.
- Gas turbine and diesel power plants are the main competitors to fuel cells in stationary applications; internal combustion engines and various hybrid powertrains are the main competitors to fuel cells in transportation.

Potential Benefits and Costs

Carbon Reductions

- The use of fuel cells leads to carbon reductions in both stationary and transportation applications. These could be significant if a fuel cell were used instead of a combustion device for fossil fuels because a fuel cell is more efficient. The reductions could be substantial if the fuel cell used hydrogen as the fuel and the hydrogen production process did not release carbon to the atmosphere. The estimated carbon reductions are accounted for in the pathways that would use fuel cells, principally: 1.2 Building Equipment and Appliances, 2.1 Industrial Energy Conversion and Utilization, 3.3 Hybrid, Electric, and Fuel Cell Vehicles, 6.2 Low-Carbon Fuels and High-Efficiency Generation, 6.3 Ultra-High-Efficiency, Zero-Carbon Emission Energyplexes, and 8.1 Biomass Electric.

RD&D Expenditures

- RD&D on fuel cells is presently conducted by DOE in FE, OTT, and OBT. This present RD&D funding and estimated RD&D expenditures in future years are accounted for in the pathways listed under Carbon Reductions. However, a modest stand-alone program funded at \$10M/year, that would undertake "generic" federal RD&D would be a valuable complement to the RD&D carried out in the various DOE offices.

Market

- Fuel cell technology has the potential to achieve large market shares in distributed power and on-site power generation as well as in light- and heavy-duty transportation.

Energy

- Making the same assumptions as earlier, the reduction in petroleum consumption for transportation could be 0.2 quads by 2010, 3.1 quads by 2020, and 6.9 quads by 2030. Energy reduction for stationary power generation could be 0.4 quads by 2010, 2.2 quads by 2020, and 6.9 quads by 2030.

Nonenergy Benefits and Costs

- Benefits would be energy security, high export potential, and a reduction in emissions of criteria pollutants. Costs would be associated with installing a non-petroleum infrastructure for transportation.

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Manufacturing cost must be reduced, and cost-effective materials are required to improve durability. Integrated systems demonstrations are needed for transportation applications. Weight and size must be reduced.

Commercial Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Currently, a fuel cell power system costs 3 to 10 times more than competing systems in stationary and transportation applications. Lack of industrial experience in designing and manufacturing fuel cells, particularly for transportation, will expose vehicle manufacturers to greater warranty and safety liability. Lack of user familiarity with fuel cell products could hinder deployment. Increased backing by the private-sector investor community is needed.

Ecological Risk

① 2 3 4 5 6 7 8 9 10

Low High

- Zero or near-zero emissions of criteria pollutants from fuel cell power systems will be the net benefit.

Human Health Risk

① 2 3 4 5 6 7 8 9 10

Low High

- Fuel cells do not pose a risk to human health.

Economic Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Large amounts of development funding are required with no assurance of success. Failure to provide funding will result in this country's having to import fuel cell technology if it is successfully developed and commercialized overseas.

Regulatory Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Recyclability of fuel cells at the end of the useful vehicle life must be considered.

Key Federal Actions

- Fuel cell development and commercialization requires long-term (10-year time frame) funding.
- Steady federal R&D funding is required to address technical barriers and develop enabling technologies.
- Government/industry partnerships are needed to further fuel cell acceptance in stationary power generation and in transportation.
- Federal procurement could stimulate demand, and incentives could facilitate purchase of fuel cell vehicles and power generators.

10.2 HYDROGEN

Technology Description

Hydrogen is a carbon-free fuel that can be used in vehicles, homes, factories, and power plants. When hydrogen is produced from nuclear or renewable electricity, CO₂ is essentially absent from the fuel cycle. When hydrogen is produced from carbon-containing primary energy sources, CO₂ appears as a concentrated byproduct; subsequent sequestration can result in low emissions of CO₂, depending on the amount of fossil energy used in the hydrogen production process. Hydrogen from biomass or solid wastes can result in very low CO₂ emissions, depending on the amount of fossil fuel used for fertilization, cultivation, transportation, and so on. Once produced, hydrogen is an environmentally benign, versatile fuel that requires efficient use technologies to be economically viable. Hydrogen can be used efficiently in the near term with conventional energy conversion devices, optimized for high efficiency and minimum emissions. In the longer term, hydrogen can be used in fuel cells, which promise potentially higher system efficiency and solid-state operation with water as the only emission.

System Concepts

- Hydrogen made from excess nuclear or renewable energy can be used as a sustainable transportation fuel and, if necessary, stored to meet peak-power demand and used as a carbon-free feedstock in chemical processes.
- Hydrogen produced by decarbonizing fossil fuels and sequestering the carbon can enable the continued, clean use of fossil fuel during the transition to a future carbon-free hydrogen economy.
- The hydrogen fuel system comprises production, storage, distribution, and use. Technologies are in various stages of development across the system.

Representative Technologies

- Hydrogen production
 - Thermochemical conversion of fossil fuels and MSW to produce hydrogen and CO₂ with the CO₂ available for sequestration.
 - Renewable (wind, solar) and nuclear electricity converted to hydrogen by electrolysis of water.
 - Photoelectrochemical and photosynthesis-based processes for producing hydrogen from water.
- Hydrogen storage
 - Pressurized gas, cryogenic liquid (commercial today) or cryogenic gas; or chemically bound as metal hydrides, adsorbed on carbon, or encapsulated in micro-capsules.
- Hydrogen distribution
 - By pipeline, by decentralized or point-of-use production using natural gas or electricity, by truck (liquid or compressed are commercially available), by distribution of hydrogen-adsorbent storage media (metal hydride, carbon, or micro-capsules).
- Hydrogen Use
 - Transportation: Used by internal combustion engines or fuel cells to power vehicles with electric power trains.
 - Potential long-term use as an aviation fuel.
 - Industrial: Useful as a reductant in metal production.
 - Power plant: Can be used as a fuel for gas turbines and steam generators in combined-cycle fossil fuel plants with carbon sequestration.

Technology Status/Applications

- Production: Hydrogen production from conventional fossil-fuel feedstocks is commercial. Large-scale CO₂ sequestration options have not been proved and require R&D. Production technologies from waste and biomass are under development. Current electrolysis technology is 60% efficient, but costly. Research is needed to increase efficiency and reduce costs.
- Storage: Experimental metal hydrides and liquid hydrogen are used in automobile demonstrations.
- Distribution: In a transitional phase, the electricity grid and the natural gas pipeline system will serve to supply primary energy to hydrogen producers. For a fully developed hydrogen energy system, a new hydrogen pipeline system is envisioned.
- Use: A PEM fuel cell-based propulsion system with on-board storage of pressurized hydrogen has been demonstrated for buses. Liquid hydrogen and hydrides combined with internal combustion engines have been demonstrated in automobiles.

Current Research, Development, and Demonstration

RD&D Goals

- By 2000, develop (1) an on-board hydrogen storage system capable of an energy density of 4 kWh/kg and a cost of \$10/kWh, (2) a process demonstrated on the 10-ton/day scale for producing hydrogen from MSW with a thermal efficiency of 50% (energy content of hydrogen/energy content of feed), and (3) a fuel cell or hydrogen-powered internal combustion engine hybrid vehicle fleet with associated infrastructure for a "clean corridor" development.
- By 2010, develop (1) photobiological and photoelectrochemical processes for hydrogen production; (2) more efficient fuel cells for transportation and distributed electric power generation; (3) advanced storage systems based on carbon structures, metal hydrides, and engineered micro-capsules capable of providing sufficient storage to meet a vehicle range of <400 miles; and (4) a conversion process for waste and biomass producing hydrogen at a cost of \$10/GJ (high heat value of hydrogen).

RD&D Challenges

- On-board storage systems that make long-range hydrogen vehicles technically and economically feasible.
- Affordable hydrogen production technology from renewable sources and CO₂ sequestration technologies to enable the use of existing domestic fossil fuel resources as a transition strategy.
- Stable and safe lean premixed combustion technologies for hydrogen-fueled power production cycle.

RD&D Activities

- DOE's hydrogen program is carried out by national laboratories, universities, and the private sector, including CRADA collaborations.
- Federal funding was \$14.5M in FY 1996 and \$15M in FY 1997 and will be \$17M in FY 1998.
- Hydrogen technology is strongly supported abroad. Federal funding in Germany is estimated at \$40M and in Japan at \$60M. Private-sector European funding exceeds \$350M in 1998.

Recent Success

- A compact process for separating oxygen from air and using the oxygen to convert natural gas to a mixture of hydrogen and CO has been demonstrated on a laboratory scale with 98% efficiency.

Recent Success (continued)

- A PEM fuel cell with a system efficiency of 46–47% and a stack power density of ~ 1 kW/l.
- Direct conversion of sunlight into hydrogen using a semiconductor-based photoelectrochemical cell was demonstrated with 8% efficiency.
- A hybrid bus configuration was demonstrated using metal hydride storage and an internal combustion engine/genset with emissions below detectable limits.
- Cryogenic pressure vessels were conceptually shown to be capable of providing 400–800 mile ranges for PNGV-class hydrogen-fueled passenger vehicles.

Commercialization and Deployment

- Hydrogen is a bulk commodity (annual U.S. production about 1 quad) today but only for “captive” use in refineries and chemical plants such as ammonia/fertilizer plants.
 - Hydrogen as a fuel is used only in niche markets such as rocket propulsion and urban bus tests.
 - Some 0.2 M tons of merchant hydrogen is produced and shipped annually in the United States.
- Currently hydrogen is provided by all major gas suppliers. In the future, the natural gas and petroleum industries are expected to expand existing hydrogen production facilities to include direct hydrogen sales.
- Pipeline companies are expected to enter the hydrogen distribution business.
- Manufacturers of fuel-cell propulsion systems are on the verge of commercializing their products.

Potential Benefits and Costs

Carbon Reductions

- The use of hydrogen could lead to carbon reductions in both stationary and transportation applications. The hydrogen can be used in a combustion device with or without a generator or in a fuel cell. The latter is preferred over the longer term because while combustion devices can be made to operate at 40% efficiencies and emit few NO_x emissions, fuel cells have higher inherent efficiency and zero emissions. The carbon reductions could be substantial if the hydrogen production process did not release carbon to the atmosphere. The estimated carbon reductions are accounted for in the pathways that would use hydrogen, principally: 1.2 Building Equipment and Appliances; 2.1 Industrial Energy Conversion and Utilization; 3.3 Hybrid, Electric, and Fuel Cell Vehicles; 6.2 Low-Carbon Fuels and High-Efficiency Generation; 6.3 Ultra-High-Efficiency, Zero-Carbon Emission Energyplexes; and 8.1 Biomass Electric.

RD&D Expenditures

- RD&D on hydrogen is presently conducted by DOE in a “stand-alone” program in OUT. The RD&D funding was \$15M in FY 1997. Estimated federal RD&D expenditures in future years are \$40M/year over each of the decades 2000–2010, 2010–2020, and 2020–2030.

Market

- The fuel markets for power generation and transportation are huge. With the expected combined market penetration, the yearly energy amounts impacted will be 3 quads in 2010, 15 quads in 2020, and 35 quads in 2030.

Energy

- A hydrogen energy system allows a gradual transition from fossil fuels to non-carbon primary energy sources while reducing CO₂ and other emissions. At full market penetration, all conventional use of fossil fuels would be replaced by hydrogen derived from renewable or carbon-sequestered fossil-fuel sources. Hydrogen would provide energy security because it can be produced efficiently from any domestic primary energy source.

Nonenergy Benefits and Costs

- Improvements in air quality wherever hydrogen replaces conventional fossil fuels.
- New hydrogen technologies, such as PEM fuel cell propulsion systems, offer new manufacturing opportunities.

Risk Factors

Technical Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Technical risk is modest because mostly known technology is deployed in a hydrogen energy system.

Commercial Risk

1 2 3 4 5 6 ⑦ 8 9 10

Low High

- Commercial risk is significant because direct use of cheap fossil fuels is a strong competitor.

Ecological Risk

① 2 3 4 5 6 7 8 9 10

Low High

- Hydrogen use is intrinsically clean.
- Fugitive hydrogen emissions are ecologically benign.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- No negative health effects are associated with exposure to hydrogen. Explosion or fire hazards are possible, but engineered controls can minimize potential hazards.

Economic Risk

1 2 3 4 5 6 ⑦ 8 9 10

Low High

- Cost of hydrogen-fueled vehicles will be higher than costs of conventional vehicles.
- Cost of hydrogen to consumer will be higher than conventional fuels.

Regulatory Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

Key Federal Actions

- Federal R&D funding enhances the technology base by addressing critical technical barriers and developing enabling technologies that are in the precompetitive stages.

10.3 SENSORS AND CONTROLS

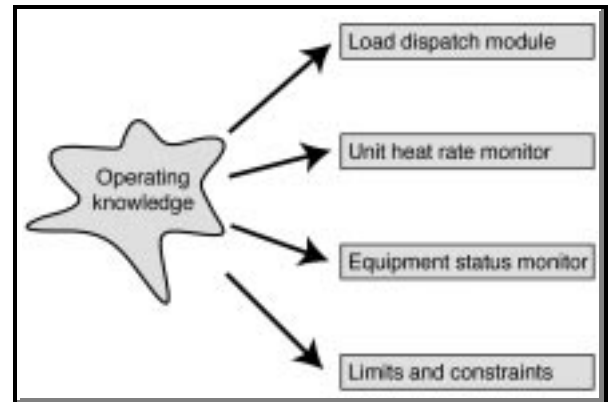
Technology Description

Sensors and controls will play an ubiquitous role in technological advances to reduce CO₂ emissions and sequester CO₂. Each of the primary areas of clean energy production, energy efficiency, and carbon cycle management will require sensors and controls technologies, either as enabling technologies to meet program requirements or as essential technologies to ensure maximum efficiency at minimal cost. For example, fossil energy extraction could be improved through chemical sensors capable of operating boreholes or through better sensor technology for mapping coal deposits. Refining processes and fossil fuel reforming for CO₂ sequestration at the wellhead both require substantial chemical processing that could be enhanced through real-time process sensors and controls. In the area of energy efficiency, novel sensors are needed in the transportation field to enable the use of more efficient engine technologies. Almost all industrial processes depend on sensors and controls to ensure the quality of goods produced. Advanced sensors could reduce wasted energy and hence CO₂ emissions. In carbon cycle management, innovative sensors are needed for analyzing photochemical processes and carbon fixation and may also be required for efficient biomass energy production.

Some underlying fundamental sensor technologies are adaptable to meet needs across different applications. An example is the solid-state oxygen sensor developed through the space program in the 1960s. It is now universally used in gasoline engine control and is common in industrial combustion control, touching virtually every major energy-consuming industry. A large variety of novel sensor technologies that are robust, sensitive, cost-effective, and capable of supporting real-time control—and the commensurate methods of data analysis and fusion for control—will be required in a successful climate change technology development program.

System Concepts

- The full extent of sensor and control technologies will span all approaches to mitigating climate change. Because of the variety of potential applications, generic system concepts are difficult to describe. An example of the system concept follows.
- Transportation is a key area where improving energy efficiency could have a significant impact on CO₂ emissions. Transportation uses over 30% of the fossil fuels burned in the United States and has a commensurate impact on CO₂ emissions. To improve the efficiency of personal transportation, new engine technology is required. Oxygen, NO_x, and knock sensors and engine control technologies will be necessary to optimize the various lean-burn internal combustion engines, compression-ignited/direct-injection engines, and diesel engines being considered to meet PNGV and other transportation goals.



Representative Technologies

- Physical sensors for in situ temperature, pressure, viscosity, flow, and other process characterization applications.
- Sensors for chemical speciation in hostile process and combustion control environments.
- Pattern recognition, artificial intelligence, fuzzy logic, and other enabling technologies for real time data analysis and “sensor fusion.”
- Sensors with embedded self-diagnostics and calibration.
- Enabling technologies that yield integrated sensors and controls systems that are fast, robust, inexpensive, miniature, and wireless.

Technology Status/Applications

- The variety of transduction methods and the capability to fabricate small, rugged, inexpensive sensor devices has advanced tremendously over the last 5 years. A recent example of high-technology sensing is the Mars probe’s miniaturized robotic instrumentation package capable of analyzing the chemical composition of rocks. Substantial effort is under way to continue to develop chemical sensor capabilities either directly through chemically active devices or indirectly through optical, acoustical, or other physical means of determining chemical composition. The development of sensors for measuring temperature, pressure, viscosity, flow, and other physical characteristics continues to be challenging. Modern techniques for fabricating electronic devices allow unprecedented miniaturization of sensors and associated electronic controls. Rapid analysis of sensor data and feedback control is also advancing, often enabled by microprocessor technology.
- The current application of sensors for industrial process control has a tremendous impact on productivity and concurrent savings in energy and CO₂ emissions. The direct impact of sensor technologies on CO₂ emissions can be illustrated by combustion control through closed-loop feedback. This approach has improved passenger vehicle efficiency by an estimated 15% and fossil fuel burner efficiency by about 3%, with commensurate decreases in CO₂ emissions.

Current Research, Development, and Demonstration

RD&D Goals

- Advanced sensors will be developed and demonstrated for chemical speciation and characterization, as well as for physical measurements. They are targeted at hostile process and combustion control environments. They will provide industrial users with reliable measurements not previously achieved in hostile field environments. In parallel, the capability to test and evaluate sensor functionality and reliability in harsh environments will be developed. We envision the creation of new sensor technologies for inexpensive physical and chemical characterization of modern industrial and chemical processes; these sensors will have embedded self-diagnostics and calibration that provide the necessary qualities of fast response, sensitivity, and robustness.

RD&D Challenges

- Technical challenges to achieving these goals include (1) materials selection and development for the capability to withstand harsh environments such as high temperature or strong acid; (2) packaging methods that allow sensitive equipment and systems to operate in destructive environments; (3) signal processing to extract useful and repeatable information from low-level, noisy measurements; and (4) methods of communication that permit whole systems of sensors and controls from multiple manufacturers to operate together with the potential for easy future upgrades. One challenge with high potential pay-off is development of sensor-level wireless communications for wide-area plant deployment.

Current Research, Development, and Demonstration (continued)

RD&D Activities

- Within DOE are small sensor and control programs generally aimed at specific objectives with some impact on CO₂ emissions. DOE's OIT funds work on exhaust gas sensors for automotive applications. OIT has requested funding for a sensors and controls initiative to support IOF and has funded a study on sensing in harsh environments.
- Numerous programs and projects are under way throughout the federal sector. A thorough analysis of recent and on-going programs should be conducted to identify relevant technologies that can be accelerated to meet CO₂ mitigation goals.

Recent Success

- A low-cost oxygen sensor developed and fabricated by a national laboratory has been incorporated into a commercial combustion control system. This sensor is being tested in industrial settings with particularly harsh smokestack environments and may enable combustion control in previously unacceptably harsh industrial settings.
- A measurement capsule developed and fabricated by a national laboratory has been incorporated in oil well drill bits. The self-contained measurement system, which withstands the harsh down-hole environment, predicts and diagnoses bit failure. The system reduces the time, costs, and lost energy related to broken bit extraction.

Commercialization and Deployment

- There are more than 4200 sensors and controls companies in the United States. Commercialization of sensor technology depends on demonstrating economic viability at a level commensurate with the risks small businesses can assume.

Potential Benefits and Costs

Carbon Reductions

- Sensors and controls technologies enable deployment of new industrial and commercial processes for reduced GHG emissions. Improved sensors and controls also allow operation closer to theoretical materials and process limits, which improves efficiency in processes such as fossil-fired power generation. The impact of sensor and control technologies on carbon reduction is difficult to state as a single estimate because of the wide variety of processes and industries that would benefit from better operation.

RD&D Expenditures

- Sensor technology is often a hidden part of DOE programs. An estimate of the current DOE OIT expenditures specifically on sensors and controls is in excess of \$15M/year. The present RD&D funding and estimated RD&D expenditures in future years are accounted for in the various Energy Efficiency and Clean Energy pathways. However, a modest stand-alone program funded at \$10M/year that would undertake "generic" federal RD&D would be a valuable complement to the RD&D carried out in the various DOE offices.

Market

- The market for improved sensors and controls, especially for harsh environments, cuts across all industries and transportation. Nuclear, fossil, renewable, and end-use efficiency technologies would all benefit.

Nonenergy Benefits and Costs

- The sensor technologies developed for energy efficiency will often lead to reductions in environmental and health risks.

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Moderate risk applies because a variety of approaches are available to address various technical challenges. Some critical fundamental technologies are yet to be developed, and within the framework of renewable energy sources, some will succeed and others may not.

Commercial Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Commercial risk is low to moderate because commercialization, especially of revolutionary technologies, requires significant investment.

Ecological Risk

① 2 3 4 5 6 7 8 9 10

Low High

- The introduction of sensor technologies is likely to have a favorable environmental impact.

Human Health Risk

① 2 3 4 5 6 7 8 9 10

Low High

- Direct impact on human health is more likely to be positive—no direct negative health affects are associated with sensors and controls technologies.

Economic Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- Cost drivers are relatively high for sensors and controls because the technologies must have a minimal negative impact on final product cost.

Regulatory Risk

① 2 3 4 5 6 7 8 9 10

Low High

- New regulations may drive the invention of new sensor technologies.

Key Federal Actions

- Provide federal R&D funding to develop key sensors and controls technologies that are generic, precompetitive, and applicable across a variety of commercial market sectors that use large amounts of energy and have a direct impact on GHG emissions.

10.4 TRANSMISSION AND DISTRIBUTION TECHNOLOGIES

Technology Description

The electric utility industry is restructuring itself into a competitive, open access marketplace. Electric power transmission and distribution (T&D) are the means whereby the benefits of this new structure will be made available to customers. Construction of U.S. transmission above 230 kV will grow by only 4.4% from 1996 to 2005. During the same period, U.S. electric energy sales are projected to grow by more than 17%. The resulting increase in the intensity of use of existing facilities will increase energy losses and transmission congestion, making it difficult for renewable generation to find a secure market position.

Energy losses in the U.S. T&D system were 7.2 % in 1995, accounting for 2.5 quads of primary energy and 36.5 MtC. Losses are divided ~60/40 between lines and transformers. Technologies that can improve efficiency and reduce carbon emissions are high-voltage dc (HVDC) transmission and power transformers and underground cables that use high-temperature superconductors (HTSs) High-efficiency conventional transformers could have significant impacts on distribution system losses. Real-time system control could improve access to customers for renewable power producers and enable greater use of environmental generation dispatch.

System Concepts

- HVDC lines are more efficient than conventional ac lines. A 250-mile 500 kV ac line converted to +/- 400kV HVDC operation would have 33% less energy loss.
- HTS cables have almost no losses except for refrigeration and can transport more than twice as much power as a conventional cable in the same size conduit.
- HTS power transformers have minimal losses, can be 50% smaller and lighter than conventional units, are nonflammable, and do not contain oil or any other potential pollutant.
- Better core materials and winding design for line transformers can cut losses dramatically.
- Real-time control using measured data and automated controllers improves T&D reliability, increasing power transfer capacity for renewable generation without new line construction.

System Components

- HVDC converter terminals use solid state power electronic switches to convert ac to dc and vice versa. Dc transmission lines have two sets of phase conductors instead of three or more.
- HTS cables consist of large numbers of tapes containing HTS materials operating at 77°K, insulated thermally and electrically. Refrigerating equipment maintains the temperature of the cable, extracting heat that manages to leak into the assembly.
- HTS transformers use the same types of materials as cables, formed into coils and mounted on conventional transformer cores. Electrical insulation may be liquid nitrogen or vacuum.
- Such advanced materials as laser-etched silicon steel or amorphous metal ribbon in the iron core of the transformer can cut distribution transformer core losses, and advanced winding techniques can reduce load losses.
- Real-time control uses wide area measurement systems, synchronized by satellite clocks to feed system information to artificial neural nets that reconfigure the system in real time, preventing system outages and permitting maximum use of available transmission capacity.

Technology Status/Applications

- HVDC: Conventional thyristor-based systems are commercially available at costs of \$220/kW for both terminals. Advanced converters have been tested in the lab.
- HTS cables: Under the DOE Superconductivity Partnerships Initiative, a team led by Pirelli Cable successfully tested a 50-m cable assembly. Southwire Company is building a 30-m prototype cable to power its manufacturing plant.
- HTS transformers: A 750-kVA three-phase low-voltage transformer is being tested in Switzerland on the grid. Waukesha Electric Systems, with partial DOE funding, is leading a team developing a 1-MVA 13-kV single-phase test unit and a 5-MVA three-phase prototype.
- High-efficiency distribution transformers are commercially available, but a cost premium of about 20% makes them unappealing to commercial and industrial users.
- Wide area measurement units without control capability have been deployed in the western United States power grid to help analyze system disturbances.

Current Research, Development, and Demonstration

RD&D Goals

- HVDC voltage source converter terminal that cost 50% less than conventional units. HVDC markets include high-efficiency line capacity upgrades on existing rights of way and a large export market in the developing world.
- HTS tapes with current densities of over 10^6 amps/cm² in kilometer lengths at costs of 90% less than current materials. Markets include \$500M/year in medium-power transformers, plus replacement or upgrading of aging urban transmission cable.
- High-efficiency transformer core steel costs must be reduced by 50% and handling/brittle fracture problems resolved. The existing distribution transformer market is \$1B/year.
- Artificial neural net training requirements must be reduced by a factor of ten. The annual market for conventional utility control systems approaches \$300M.

RD&D Challenges

- HVDC: To achieve a cost reduction goal of 50%, high-voltage, self-commutating converters. Switching devices made of silicon carbide or diamond are a long-term challenge.
- HTS cables and transformers: The manufacture of promising HTS materials in long lengths at low cost. Materials for cryogenic insulation high-efficiency refrigerators are also required.
- Improved ductility of amorphous metal core steel and high-strength, low-loss winding materials for reduced costs in the manufacture of high-efficiency distribution transformers.
- Neural net networks that can be trained in parallel.

Current Research, Development, and Demonstration (continued)

RD&D Activities

- HVDC: There is no active U.S. program for HVDC development. EPRI spends \$3M to \$5M/year on high-voltage power electronics for the related Flexible AC Transmission System technology. HVDC R&D is taking place at offshore manufacturers aimed at sales in India, China, and South America.
- HTS: DOE funding of HTS utility technology is \$19M/year, plus an industry cost share of \$8M/year. Germany and Japan each are spending \$50M to \$100M/year each to develop HTS power equipment.
- No active research program is under way on improved distribution transformer technologies. EPRI terminated its program on improvements in amorphous metal core materials in 1995. Allied Signal (the inventor of amorphous metal transformer core material) and an Indian transformer manufacturer have agreed to develop and manufacture high-efficiency transformers in India for the burgeoning Asian market.

Recent Success

- The development of RABiTS™ and IBAID technologies for producing high-performance HTS film conductors suitable for cables and transformers, and the involvement of four industry-led teams to capitalize on it, was a major success story for FY 1797.

Commercialization and Deployment

- Conventional HVDC using thyristor valves is a mature commercial niche product with 30GW of installations in North America. No expansion is anticipated in North America unless cost reduction targets are achieved. The market in China and India may be up to 100GW.
- HTS cables and transformers: Commercial deployment awaits improved HTS materials and reduced costs in their manufacture and application.
- High-efficiency distribution transformers have been offered on the U.S. market for over 15 years, but sales have been declining and manufacturers are leaving the market as purchasers move to lower-cost, lower-efficiency transformers.

Potential Benefits and Costs

Carbon Reductions

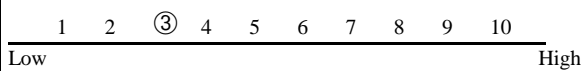
- T&D is crosscutting in that it links electrical generation technologies to energy end-use technologies. The carbon reductions attributed to T&D are only those of an improved T&D system itself. They are estimated to be 3–4 MtC/year in 2010, 5–6 MtC/year in 2020, and 20–25 MtC/year in 2030.
- Export markets are likely to generate significant savings, but these have not been estimated. Savings do not take into account the effect of secondary benefits such as the enabling of additional renewable generation.

R&D Expenditures

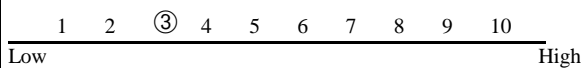
- RD&D on HTS is conducted by OUT at the level of \$19M in FY 1997. Of this amount, \$12M can be roughly attributed to HTS for T&D. There is no other DOE funding for T&D. Estimated federal RD&D expenditures in future years for the broader program described in this pathway are \$25M/year over 2000–2020 and \$20M/year over 2020–2030.

Risk Factors

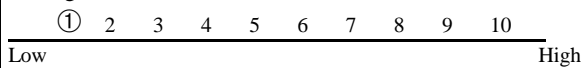
Technical Risk



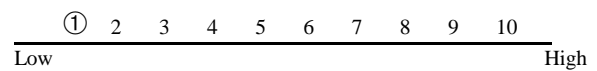
Commercial Risk



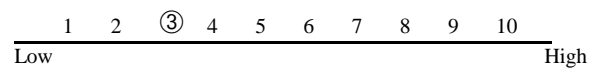
Ecological Risk



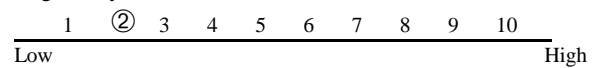
Human Health Risk



Economic Risk



Regulatory Risk



Key Federal Actions

- A T&D research initiative could be developed to fund HVDC, HTS, and other T&D technologies. The aim of the federal program could be to develop advanced concepts in conjunction with demonstrations by industrial partners.

10.5 POWER ELECTRONICS AND ELECTRIC MACHINERY

Technology Description

Power electronics is the technology used to convert one form of available electrical power to the form required by the application. About 60% to 70% of the nations' electrical power is used to drive motors, and motors are reasonably efficient at rated speed and load. But efficiencies can be tremendously improved by operating motors at variable speeds to match the system requirements or by replacing the copper wires with high-temperature superconducting (HTS) wires. Motors driven by power electronics to achieve variable speed capability are increasing dramatically in numbers as the technologies become available. Power electronics devices with higher power handling capability and reliability are being developed, enabling more widespread use. HTS motors would pay for themselves in energy savings over the life of the motor because of improved efficiency. Coupled together, inverter-driven HTS motors offer an unprecedented opportunity for U.S. industry and utilities to reduce energy consumption and improve competitiveness.

System Concepts

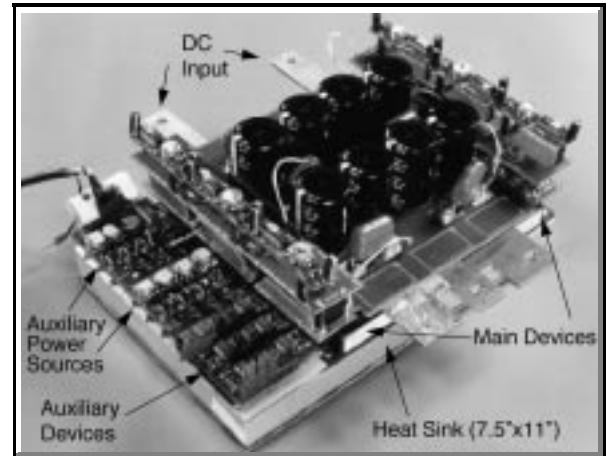
- Advanced inverter topologies: Inverter circuitry that accommodates and takes advantage of advanced solid-state devices while further improving the overall efficiency, packaging, and performance of the inverter.
- Advanced electric machinery: Various type of electric motors and generators that are better suited for particular applications, that are more cost-effective, or that provide for the use of new technologies such as HTS wire.

Representative Technologies

- Soft switching inverters, multi-level inverters, buck/boost converters, induction motors, permanent magnet motors, variable reluctance motors, materials for improved power electronics and electric machinery, superconducting electric motors and generators.

Technology Status/Applications

- Transportation: Displacement of internal combustion engines and an enabling component of alternate approaches to vehicle systems (traction drives, flywheels, auxiliary drives, alternators).
- Industrial: More efficient motors and introduction of adjustable speed drives to match drives to loads for fans, pumps, and compressors.
- Defense: "More electric" initiatives by various branches of the military.
- Utilities: Power quality systems, HTS motors, high-voltage dc transmission systems.
- Renewable energy: Inverters to convert photovoltaic power to ac power
- Power supplies: Converters embedded in systems to alter the electrical power from one type to another.



Resonant snubber inverter power converter

Current Research, Development, and Demonstration

RD&D Goals

- Develop HTS wires with engineering current density of $>50,000$ A/cm² in a field of 2-5 Tesla in liquid nitrogen, with a cost of \$10–100 per kA/m.
- Develop and demonstrate a pre-commercial prototype 1000-hp HTS motor by FY 1999.
- By 2004, under PNGV improve motor efficiency from 85% to 96% and inverter efficiency from 92% to 98%.
- Develop more electric aircraft, military land vehicles, and ships
- By 2008, develop a power electronics building block capable of dramatically improved power density, efficiency, and cost.

RD&D Challenges

- Smaller, lighter, more efficient, lower cost inverters and motors are required.
- Reliability, cost, and electromagnetic compatibility must be improved.
- Improved materials for power electronics systems and for HTS electric machinery are required.

RD&D Activities

- Navy/ONR and DOE joint program to develop power electronic building blocks.
- Military developments of "more electric" aircraft, ships, and land vehicles.
- PNGV is pursuing the development of electric machinery and drives as an enabling technology.
- The federal initiatives in transmission and distribution system long-range R&D were canceled.
- The Superconductivity Technology Program funds R&D of more efficient motor technology under the Superconductivity Partnership Initiative.

Recent Success

- Soft-switching inverter topologies have been recently developed for improved inverter efficiency, reliability, and performance.
- High-power solid-state inverters with improved efficiency and reduced cost and size have been developed.
- A multi-level inverter has been developed which when deployed will allow 26% more energy to be extracted from photovoltaic or other renewable energy sources.
- Superconducting Machinery: Under the DOE's Superconductivity Partnership Initiative, Rockwell Automation demonstrated a prototype 200-HP synchronous motor, and is now designing a 1000 HP motor, to be operational in 1999, and a 5000-HP motor, to be operational in 2001. In 1996 General Electric Co. produced a prototype HTS generator coil.

Commercialization and Deployment

- USCAR has been formed so that Ford, GM, and Chrysler can better implement technologies developed under PNGV.
- Major U.S. motor and drive manufacturers are beginning to expand their product lines to include higher efficiency motors and improved power electronics. Superconducting motor prototypes are being produced by Rockwell Automation.
- U.S. power semiconductor manufacturers are expanding product lines and facilities to regain market position from foreign competitors.
- DOE Motor Challenge Program is actively promoting the use of efficient electric machinery in industry.

Potential Benefits and Costs

Carbon Reductions

- The use of improved power electronics and electric machinery leads to carbon reductions in virtually all electrical generation technologies and energy end-use technologies. Correspondingly, the estimated carbon reductions are accounted for in the Energy Efficiency and Clean Energy pathways.

RD&D Expenditures

- RD&D on HTS is conducted by OUT at the level of \$19M/year in FY 1997. Of this amount, \$7M can be roughly attributed to HTS for Power Electronics and Electric Machinery. Because current DOE funding is not carefully coordinated among its various offices, it is difficult to ascertain the exact level of other DOE funding in this area. The present spending and estimated future RD&D expenditures in these offices (other than HTS) is accounted for in the other pathways. Estimated expenditures on HTS plus a modest stand-alone program that would undertake "generic" federal RD&D are \$20M/year over 2000–2020, and \$15M/year over 2020–2030.

Energy

- OIT estimates that by 2010, annual savings in U.S. industry from more efficient industrial electric motor systems could be roughly 240 billion kWh/year and up to 50,000 MW of avoided new power plant capacity.
- Directly replacing all motors of over 125 hp with superconducting motors would save U.S. industry \$1.34B annually in electric costs. Assuming only motors rated at greater than 1000 hp are replaced, annual savings would be \$420M.
- Electric generator loss reductions through the use of superconducting generators would amount to 36B kWh, or over \$1.1 billion.

Market

- According to the report from the 4th International Superconductivity Industry Summit, by the year 2010 the annual worldwide market for products based on superconductors and sold to the electric power industry is expected to generate approximately \$12B in revenues.
- Based upon the value of the energy savings cited, the market for these new technologies is huge. If \$13B per year can be saved in energy alone, then the market for the products to accomplish that should be related to the value of the energy savings.

Nonenergy Benefits and Costs

- Reduced air pollution.
- International competition.
- HTS motors and generators will be approximately half the size and weight of today's electric machinery, potentially reducing installation costs and reducing the amount of the raw materials used to produce these machines. In addition, superconducting-type ac synchronous generators may have special electrical grid system advantages, such as improved steady-state voltage regulation.

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Technologies must be developed to reduce size, weight, and cost while improving performance and reliability.

Commercial Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- New technologies must be introduced in well-known, reliable systems. Previous attempts to commercialize adjustable speed drives were somewhat unreliable, and a stigma has already been created

Ecological Risk

① 2 3 4 5 6 7 8 9 10

Low High

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- High voltage in automobiles presents a risk. Electronic circuit boards and lead solder present some risk.

Economic Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- Promotes extensive cost savings at little risk

Regulatory Risk

① 2 3 4 5 6 7 8 9 10

Low High

- None is known that would impede these technologies.

Key Federal Actions

- Federal R&D funding enhances the technology base by addressing critical technical barriers and developing enabling technologies that are in the pre-competitive stages.
- Government/industry partnerships ensure commercialization of technologies developed in long-range R&D programs.
- A government-wide power electronics initiative has been proposed to Congress but had not been acted upon as of February 1998.

10.6 ENERGY STORAGE

Technology Description

Advanced storage technologies under active development include processes that are mechanical (flywheels, pneumatic), electrochemical (advanced batteries, reversible fuel cells, hydrogen), and purely electrical (ultracapacitors, superconducting magnetic storage). Adding any advanced storage device to the utility grid usually *increases* CO₂ production because of the less-than-100% efficiency. The greatest value of advanced energy storage for utilities is that it can enable the use of intermittent renewable energy sources, such as solar PV and wind, that produce no direct CO₂. In light-duty vehicles, both all-electric battery-powered and hybrid powertrains that use batteries, flywheels, or ultracapacitors in conjunction with an engine enable the capture of much of the kinetic energy of the vehicle through regenerative braking during deceleration. In the hybrids, further efficiency improvements may be realized by reducing the engine size and using the energy storage to assist in acceleration.

System Concepts

- **Utilities:** The efficiency of a typical steam plant falls from about 38% at peak load to 28–31% range at night. Utilities would store electrical energy at off-peak times, allowing power plants to operate near peak efficiency. The stored energy would be used during peak demand times. CO₂ emissions would be reduced if the efficiency of the energy storage were greater than 85%. Battery-powered electric vehicles could serve as the off-peak energy storage system, but higher turn-around efficiency than the 70% of lead-acid batteries is needed. In the long term, as demand grows, renewable sources would be added to the grid that would use the same storage to achieve dispatchable power for peaking.
- **Vehicles:** Energy storage in automotive electric and hybrid drive trains allows regenerative braking, which can reduce fuel consumption by 25% on the urban driving cycle. Additional optimization of engine size in hybrids to allow better average-power matching could improve total powertrain efficiency by a factor of 2 over existing automobiles. Energy storage and power density for automotive applications must be lightweight (of the order of 10–20 W-h/kg and 2 kW/kg) and have high cycle life (100,000s of cycles). Bus and delivery heavy-duty vehicles can also benefit from hybrid powertrains, although the improvement is not likely to be as great as for automobiles.
- **Home cogeneration:** Small amounts of energy storage are a pathway to commercially viable home cogeneration using solid oxide fuel cells or optimized engines coupled to small generators that are fueled with natural gas. Storage of a few kilowatt-hours with power output of 5–10 kW would reduce the start-stop cycles on the fuel-to-electricity converter. Waste heat from the converter would be used for space heating and domestic hot water. Such systems could use 70–90% of the fuel energy, depending on seasonal heating requirements. If the fuel converter had greater efficiency than central power plants, these systems could be connected to the grid to carry out distributed power peaking.

System Components

- For utility applications: the energy storage system consists of power conditioning to convert the power into the form required, the storage device, and the reconversion device. For vehicles and home cogeneration applications, power conditioning, the storage device, reconversion device, and safety containment are the major components.

Representative Technologies

- For utilities, the most mature storage technology is hydro pumped storage; however, it requires elevation changes and thus is not practical in many locations. Superconducting magnetic energy storage (SMES) is under active development by the Japanese in the 100 kWh range. Zinc-ferricyanide fuel cells are not under development but have the potential for 80–90% turn-around (output/input energy) efficiency. For vehicle applications, advanced batteries, flywheels, pneumatic storage, and ultracapacitors are under development. The U.S. Advanced Battery Consortium (USABC) is developing batteries for electric-drive vehicles; about a dozen companies are actively developing flywheels; pneumatic storage is feasible for energy storage on the order of 0.1 kWh; and ultracapacitors have recently become commercially available in prototype units.

Technology Status

Technology	Efficiency [%]	Energy density [W-h/kg]	Utilities		Comments
			Power density [kW/kg]	Sizes [MW-h]	
Pumped hydro	75	0.27/100 m	low	5,000–20,000	37 existing in US
Compressed gas	75	Ñ	low	250–2,200	1 US, 1 German
SMES	90+	Ñ	high	10,000 (goal)	research mostly Japan
			Vehicles		
Batteries	70–84	30–50	0.2–0.4	17–40	USABC, development
Flywheels	90+	15–30	1–3	0.1–2.0	US & foreign development
Ultracapacitors	90+	2–10	0.5–2	0.1–0.5	Maxwell Technologies

Current Research, Development, and Demonstration

RD&D Goals

- Utilities require high reliability, ≥85% efficiency, and per-kilowatt costs less than or equal to those of new power generation (\$400–600/kWh). Compressed gas energy storage can cost as little as \$1–5/kWh, while pumped hydro ranges from \$10–45/kWh. SMES has targets of \$150/kWh and \$275/kWh. Vehicles require storage costs on the order of \$300 to 1000/kWh to achieve significant market penetration.

RD&D Challenges

- The major hurdle for all storage technologies is cost reduction. Superconducting cable design for stability and low loss is an important research area for existing NbSn superconductors. High-temperature (liquid-nitrogen temperatures) superconductors that are manufacturable and can carry high currents could reduce both capital and operating costs for SMES. Flywheels need further development of fail-safe designs and/or lightweight containment. Magnetic bearings could reduce parasitic loads and make flywheels attractive for small uninterruptible power supplies and as a major player in home cogeneration systems. Ultracapacitor development needs improved energy density from the current 1.9 W-h/kg for light-duty hybrid vehicles. Advanced higher-power batteries with greater energy storage and longer cycle-life are necessary for significant electric vehicle market penetration.

Current Research, Development, and Demonstration (continued)

RD&D Activities

- The Japanese are spending about \$5M/year for a 5-year SMES project to build a 100-kWh prototype. Superconducting coils for this project are being tested at LLNL. In a joint DOE/EPRI project, Babcock & Wilcox is building a 500-kWh SMES unit in Alaska for power quality (not dedicated storage) at a cost of more than \$20M. DOE's Energy Storage Systems Program (\$4M/year) works on improved and advanced electrical energy storage for stationary (utility, customer side, and renewables) applications. It focuses on system integration using near-term components, field evaluations, advanced component development, and systems analysis. DOE also funds research on ultracapacitors for hybrid vehicles at \$2M. This work is being done by a number of universities and industrial partners. USABC is spending approximately \$7M/year on advanced battery development for hybrid vehicles. The flywheel storage program for vehicles was funded by DOE at \$600,000 in FY 1997 and is expected to grow to about \$1.2M. The Defense Advanced Research Programs Agency is supporting flywheel containment development at about \$2M/year in a joint effort with U.S. flywheel manufacturers.

Commercialization and Deployment

- For utilities, only pumped hydro has made a significant penetration with approximately 37 GW.
- There are 140 battery/diesel hybrid buses produced by Hino in Japan.
- GM has recently started leasing a lead-acid battery electric vehicle, soon to be upgraded to higher-performance nickel-metal hydride batteries.

Potential Benefits and Costs

Carbon Reductions

- The use of energy storage devices can lead to carbon reductions in both stationary and transportation applications. The reductions can be significant if a storage device enables a renewable or other low-carbon electricity generation technology, or a hybrid vehicle with a smaller and more efficient power source. The estimated carbon reductions are accounted for in the pathways that would use energy storage devices, including 1.2 Building Equipment and Appliances; 3.3 Hybrid, Electric, and Fuel Cell Vehicles; 8.2 Wind; 8.3 Solar Photovoltaics; and 8.6 Solar Thermal.

RD&D Expenditures

- RD&D on energy storage devices is conducted by DOE in OTT, OUT, and other offices. This present RD&D funding and estimated federal RD&D expenditures in future years are accounted for in the pathways such as those listed under Carbon Reductions. However, a modest stand-alone program that would undertake "generic" RD&D would be a valuable complement to the RD&D carried out in the various DOE offices. The estimated federal RD&D expenditures are \$25M/year over 2000–2020, and \$20M/year over 2020–2030.

Energy

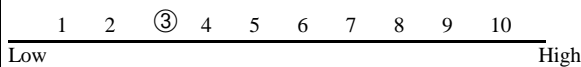
- Fuel efficiency improvements of 2–5% in the utilities (coal and natural gas savings); potential 20–30% improvement in residual efficiency using cogeneration (natural gas); potential 50% savings of petroleum in light-duty vehicles (represents 50% reduction in oil imports).

Nonenergy Benefits and Costs

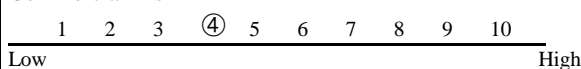
- Large-scale storage for utilities enables intermittent renewables to come to the marketplace as dispatchable power.

Risk Factors

Technical Risk

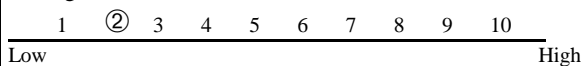


Commercial Risk

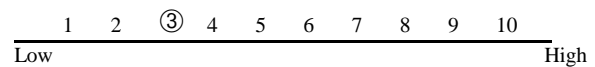


- SMES is high, flywheels moderate, and ultracaps low.

Ecological Risk

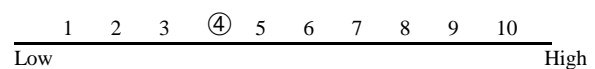


Human Health Risk



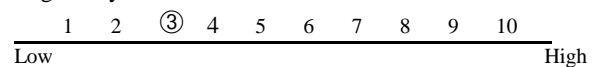
- SMES and ultracaps are low, and flywheels are moderate.

Economic Risk



- SMES is high, flywheels and ultracaps are low.

Regulatory Risk



Key Federal Actions

- Support the suggested R&D funding plan.
- Study the potential impact of requiring that any expansion of utility energy production be based on total life-cycle cost, including fuel and potential rises in fuel cost.
- Study the potential impact of requiring that at least 5% of any added utility power production expansion be renewable.
- Undertake a joint study between the auto industry and DOE of the effect of raising the CAFE standard for all light-duty vehicles by 0.5 mpg per year for the next 20 years (resulting in 37.5 mpg in 2018).

10.7 MODELING, SIMULATION, AND ANALYSIS

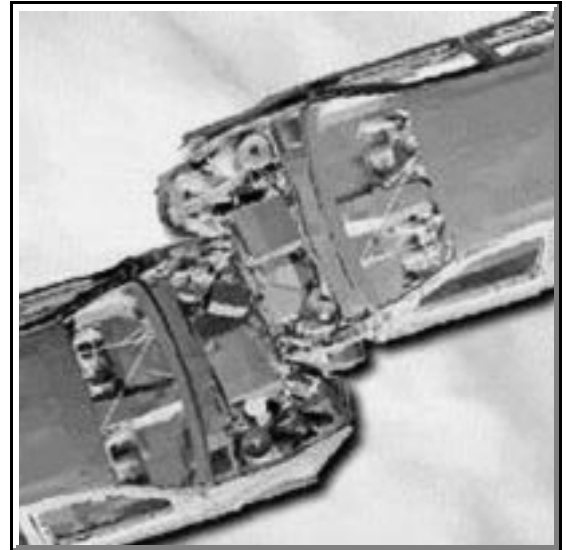
Technology Description

Modeling, simulation, and analysis technologies are critical to the successful development and implementation of any climate change technology strategy. For example, it is necessary to be able to develop and apply complex models in order to (1) understand the impact of new technologies or policies on the economy and the environment, (2) evaluate the potential for new technologies to meet GHG reduction goals, and (3) aid in the design and development of new and more efficient energy production, conversion, storage, distribution, and end-use technologies. Mathematical modeling can greatly impact the design of experiments, cost-effective field and production management, and design of remediation strategies and risk assessment. These activities will also facilitate U.S. priorities such as international trading of GHG emissions.

Advanced energy technologies with low carbon emissions can benefit greatly from modern simulation technology. Predictive modeling and simulation involves the use of the most advanced parallel computers—in speed, memory capacity, and I/O capability. High-performance computers also provide the first real opportunity for linkages and couplings among atmospheric, surface water, and groundwater processes. Advanced visualization and analysis techniques will be necessary for scientists and decision makers to understand the large-scale, nonlinear impacts that changing fuel sources, energy conversion technologies, and energy demand patterns will have on economic health.

System Concepts

- **Scientific modeling/complex systems:** High-fidelity simulations of manufacturing and power generation operations and the distribution of gases resulting from internal combustion engines can be used to predict the behavior of pollutants in the atmosphere at scales ranging from a few rooms in a building all the way up to global simulation of the buildup of GHGs. The computational capabilities allow more realistic modeling to provide an understanding of the scaling of mechanisms from the micro-scale to the macro- to mega-scale. Process design and optimization using simulations of complex systems that include social and economic components can result in improved processes and reduced environmental impacts, without the expense of trial-and-error experimental designs. These tools can aid the development of advanced energy technologies by allowing advanced modeling, steering (i.e., real-time adjustment), and visualization of computational experiments where direct experimentation or prototyping is very expensive, inaccessible, or otherwise unfeasible.
- **Life-cycle assessment of economic and environmental impacts:** The overall viability of new technologies will depend not only on the contribution those technologies make to GHG reductions. They also must be cost-effective and without adverse environmental impacts compared with the technologies or systems they are intended to replace.
- **Portfolio analysis:** A climate change technology strategy must maintain a balanced portfolio of R&D. Innovative tools (e.g., decision analysis) are needed to allow decision makers to assess whether the R&D portfolio is adequately meeting the climate change goals. Modeling and analysis will aid in prioritizing candidate research and technology.



Simulation of an automobile collision to assess the performance of lightweight materials.

Representative Technologies

- Computer speed has advanced to the point where, by the year 2000, U.S. vendor systems will be capable of 10 trillion floating point operations per second. New, innovative software and tools for distributed and parallel computing will harness the power of this computing technology to reduce development time, identify applications of new technologies, project technology contributions to GHG reductions, and promote the adoption of GHG-reducing technologies via innovative public/private sector partnerships.

Current Research, Development, and Demonstration

RD&D Goals

- Improve global carbon cycle models to minimize uncertainties. Improve resolution to determine regional and local effects.
- Improve the sophistication of energy/economic models, as well as information integration tools, to integrate individual technological processes, emissions characterization, global weather pattern simulation, and key socioeconomic and behavioral elements.
- Improve models to guide processing and aid in developing totally new approaches to manufacturing. Use of these models can reduce GHG emissions and provide new avenues for enhanced processing and manufacturing efficiency.
- Improve the understanding and modeling of combustion processes in manufacturing—a critical need for recovery boilers, furnaces, and direct-fired heat exchangers.

RD&D Challenges

- Develop new conceptual and mathematical models that more accurately reflect complex physical, biological, cognitive, behavioral, social, economic, and decision-making processes.
- Develop general and accurate nonlinear numerical algorithms describing the physical models for emissions of GHGs. In addition, efficient solution techniques that scale well on massively parallel computers and/or networks of workstations are needed to handle fine grid resolutions.

Current Research, Development, and Demonstration (continued)

RD&D Activities

- **Simulation codes:** Examples include high-fidelity simulations of manufacturing and power generation operations and hybrid-electric vehicle design codes that optimize designs to reflect efficiency goals.
- A novel methodology for evaluating the performance of advanced lightweight materials for automotive applications is being developed.
- **Energy/economic/environmental modeling:** EIA has developed and continues to improve the National Energy Modeling System (NEMS), which models the stocks of energy resources and their flows into the economy. The NEMS is used to predict energy pricing under a variety of system constraints (e.g., economic incentives) and the effects of various policies on environmental impact.
- **Life-cycle assessment:** Several modeling tools have been developed to evaluate the life-cycle costs and environmental impacts of energy production and use technologies.
- **Collaborative technologies:** Collaborative Management Environment investigates and develops information modeling and integration techniques to integrate scientific, engineering, and economic information across the DOE complex.

Recent Success

- A collaborative steering system (CUMULVS) was developed and demonstrated for computationally intensive combustion simulation across distributed sites among DOE laboratories and industrial collaborators.
- A state-of-the-art model has been developed to optimize processing parameters for producing materials with designed microstructures, thus reducing energy consumption, processing costs, and materials waste.
- Models of human behavior and cognition have been developed for advanced process control environments (nuclear power plant operation and maintenance).

Commercialization and Deployment

- Models developed with public funds are typically introduced into the public domain or licensed, making them available for use. Some tools may be used in international settings to promote the use of GHG emissions trading and joint implementation.

Potential Benefits and Costs

Carbon Reductions

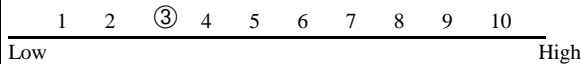
- The use of modeling, simulation, and analysis is ubiquitous among the DOE offices since it can be the key to successfully developing and implementing new classes of energy technologies. The various pathways implicitly assume such activities are a vital part of the RD&D. The carbon reductions attributed to a given pathway thus take into account the modeling, simulation, and analysis activities appropriate for that pathway.

RD&D Expenditures

- Modeling, simulation, and analysis are presently conducted in virtually all DOE offices. The present RD&D funding and estimated RD&D expenditures in future years are accounted for in the corresponding pathways. However, a modest stand-alone program that would undertake “generic” RD&D would be a valuable complement to the current work. Computational materials science, process design and optimization, and portfolio analysis that can be applied to a broad spectrum of energy technologies merit this stand-alone effort. The incremental estimated federal RD&D expenditures are \$15M/year over 2000–2030.

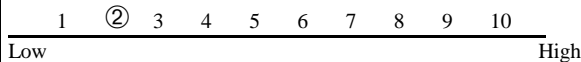
Risk Factors

Technical Risk



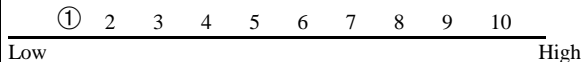
- Complex integrating systems modeling hold some technical risk. Some tools and approaches already exist.

Commercial Risk

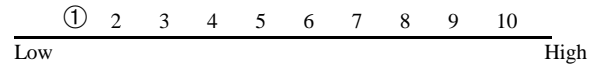


- Some of the tools will require access to high-performance computers. Tools will be available in the public domain.

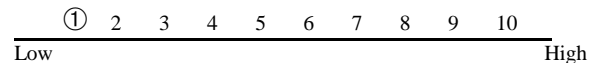
Ecological Risk



Human Health Risk

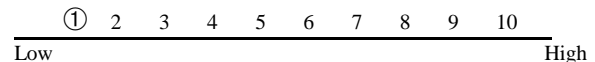


Economic Risk



- Will improve the portfolio selection process, facilitating optimal selection of technologies for development, transfer, adoption, and use.

Regulatory Risk



Key Federal Actions

- Greater use of simulation and modeling in R&D to facilitate and expedite solutions.
- Greater use of analysis and modeling in federal decision making.
- Development and demonstration of innovative public-private partnerships.

ACRONYMS AND INITIALISMS

ac	alternating current
AFV	alternative fuel vehicle
AHTS	Advanced Hydropower Turbine System
AIM	Advanced Industrial Materials Program
ARPA	Advanced Research Projects Agency
ARS	Agricultural Research Service
ATP	Advanced Technology Program
ATS	advanced turbine system
B	billion
BAU	business as usual
bb1	barrel
BES	Basic Energy Sciences
BNL	Brookhaven National Laboratory
BWR	boiling water reactor
CAFE	corporate average fuel economy
CFC	chlorofluorocarbon
CO	carbon monoxide
CRADA	cooperative research and development agreement
CSREES	Cooperative State Research Extension and Education Service
CVT	continuously variable transmission
dc	direct current
DFSS	dedicated feedstock supply system
DISC	direct-injection, stratified-charge
DNA	dioxyribonucleic acid
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOE/EERE	DOE Office of Energy Efficiency and Renewable Energy
DOT	Department of Transportation
DP	Defense Programs
EE	Energy Efficiency
EPA	U.S. Environmental Protection Agency
EPAct	Energy Policy Act
EPRI	Electric Power Research Institute
ER	Energy Research
EV	electric vehicle
FE	Fossil Energy
FETC	Federal Energy Technology Center
FRA	Federal Railroad Administration
FY	fiscal year
GDP	gross domestic product
GE	General Electric
GHG	greenhouse gas

GHP	geothermal heat pump
GIS	geographic information system
GM	General Motors
GRI	Gas Research Institute
GSA	General Services Administration
GTL	gas to liquids
GW	gigawatt
GWe	gigawatt electric
GWh	gigawatt hour
HCFC	hydrochlorofluorocarbon
HEV	hybrid electric vehicle
HF	HF and sulfuric acid processes
HIPPS	high-efficiency power systems
HSR	high-speed rail
HVAC	heating, ventilating, and air-conditioning
IBS	intelligent building system
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
keV	kiloelectron volt
kW	kilowatt
LEBS	low-emission boiler systems
LIDAR	light detection and ranging
LNG	liquified natural gas
LLNL	Lawrence Livermore National Laboratory
low-E	low-emissivity
LWR	light water reactor
M	million
Maglev	magnetic levitation
Mcf	million cubic feet
MEC	model energy code
MOU	memorandum of understanding
MPG	miles per gallon
MSW	municipal solid waste
MtC	million tonnes of carbon
MW	megawatt
MWe	megawatt electric
MWh	megawatt hour
MWth	megawatt thermal
NASA	National Aeronautics and Space Administration
NCC	National Climate Center
NEXTEA	National Economic Crossroads Transportation Efficiency Act
NIF	National Ignition Facility
NIST	National Institute of Standards and Technology
NMI	National Maglev Initiative
N _{ox}	oxides of nitrogen
NRC	Nuclear Regulatory Commission

NREL	National Renewable Energy Laboratory
NRL	Naval Research Laboratory
NSF	National Science Foundation
OBES	Office of Basic Energy Sciences
OECD	Organization for Economic Cooperation and Development
OIT	Office of Industrial Technologies
OTT	Office of Technology Transfer or Office of Transportation Technology
OUT	Office of Utility Technologies
PEM	proton exchange membrane
PFBC	pressurized fluidized bed combustion
PM	particulate matter
PNGV	Partnership for a New Generation of Vehicles
PPG	Pittsburgh Plate Glass
PRSE	performance/reliability/safety/emissions
PV	photovoltaic
PVMat	Photovoltaics Manufacturing Initiative
PWR	pressurized water reactor
QM	QM 98 study
R&D	research and development
RD&D	research, development, and demonstration
rf	radio frequency
ROI	return on investment
RRC	rolling resistance coefficient
scf	standard cubic feet
Tcf	trillion cubic feet
TDI	turbocharged direct injection
TVA	Tennessee Valley Authority
USDA	U.S. Department of Agriculture
VVC	variable valve control
W_p	Watts of power