Crosscutting Technologies

10. Crosscutting

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10.1 FUEL CELL SYSTEMS FOR STATIONARY AND TRANSPORTATION APPLICATIONS

Technology Description

Fuel cells are devices that change chemical energy directly into electrical energy without any combustion. Operating on hydrogen, a fuel cell does not emit CO_2 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.

System Concepts

- A fuel cell power plant typically consists of three main parts:
  - 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.

Representative Technologies

- 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.

Technology Status/Applications

- 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

RD&D Goals

- 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.

RD&D Challenges

- 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.

RD&D Activities

- 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

- 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

- 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, CO_2 is essentially absent from the fuel cycle. When hydrogen is produced from carbon-containing primary energy sources, CO_2 appears as a concentrated byproduct; subsequent sequestration can result in low emissions of CO_2, depending on the amount of fossil energy used in the hydrogen production process. Hydrogen from biomass or solid wastes can result in very low CO_2 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 CO_2 with the CO_2 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 CO_2 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 CO_2 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 CO_2 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

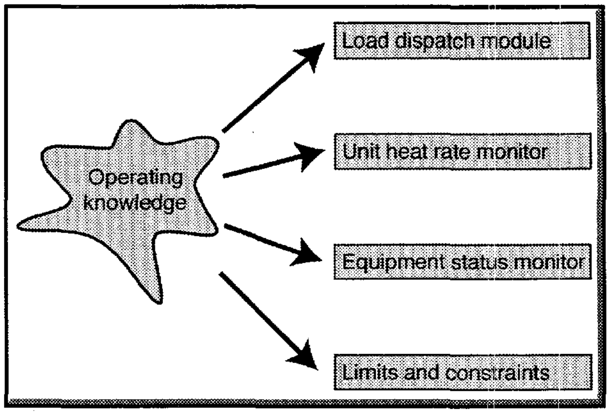
- Federal R&D funding enhances the technology base by addressing critical technical barriers and developing enabling technologies that are in the precompetitive stages.

10.3 SENSORS AND CONTROLS

Technology Description

Sensors and controls will play an ubiquitous role in technological advances to reduce CO_2 emissions and sequester CO_2. 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 CO_2 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 CO_2 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 CO_2 emissions. Transportation uses over 30% of the fossil fuels burned in the United States and has a commensurate impact on CO_2 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 CO_2 emissions. The direct impact of sensor technologies on CO_2 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 CO_2 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 CO_2 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 CO_2 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/cm^2 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 IBAD 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

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

Commercial 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

Ecological 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

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

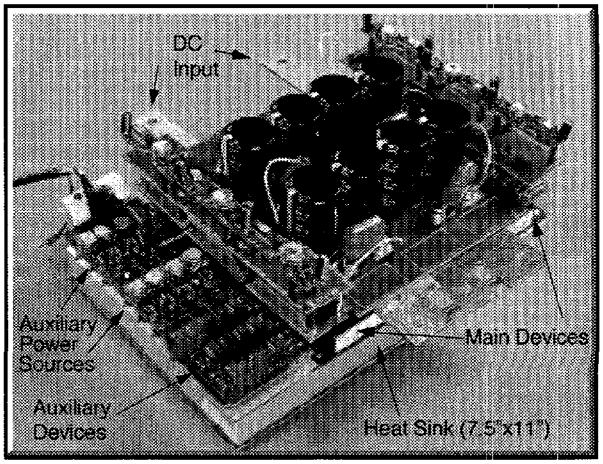
- Advanced inverter topologies: Inverter circuitry that accommodates and takes advantage of advanced solid-state devices while further improving the overall efficiency, packaging, and performance of the inverter.
- Advanced electric machinery: Various type of electric motors and generators that are better 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/cm^2 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* CO_2 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 CO_2. 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. CO_2 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]	Power density [kW/kg]	Sizes [MW-h]	Comments
			Utilities		
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/kW). 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/kW 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

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

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

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

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

Economic Risk

1 2 3 ④ 5 6 7 8 9 10

Low — High

- SMES is high, flywheels and ultracaps are low.

Regulatory Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

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

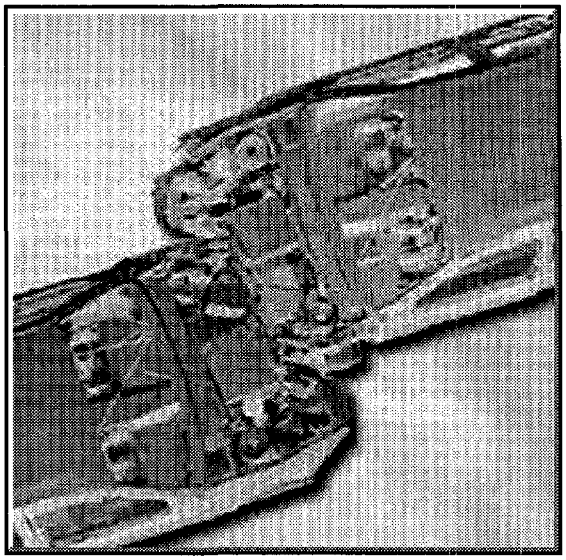
Technology Description

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 aide 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

1 2 ③ 4 5 6 7 8 9 10

Low High

- Complex integrating systems modeling hold some technical risk. Some tools and approaches already exist.

Commercial Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- Some of the tools will require access to high-performance computers. Tools will be available in the public domain.

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

- Will improve the portfolio selection process, facilitating optimal selection of technologies for development, transfer, adoption, and use.

Regulatory Risk

① 2 3 4 5 6 7 8 9 10

Low High

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.