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

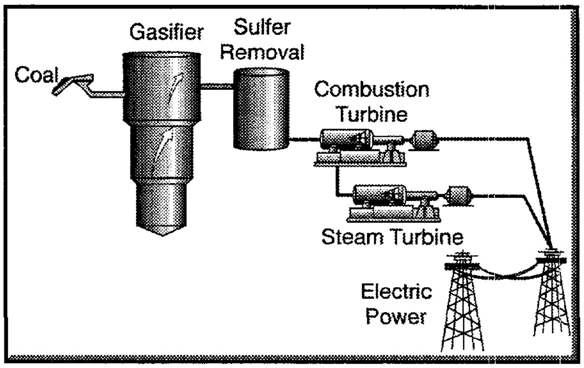
6.1 ACCELERATED DEVELOPMENT OF HIGH-EFFICIENCY COAL-BASED POWER GENERATION TECHNOLOGIES

Technology Description

This pathway will accelerate the development and deployment of high-efficiency coal power generation technologies by 3 to 5 years, reducing CO_2 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 CO_2 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 CO_2-neutral biomass fuels with coal and to accommodate other low-cost approaches for CO_2 reduction. Although this pathway assumes no CO_2 sequestration, future development of CO_2 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, CO_2 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 CO_2 capture in the next 20 years, systems deployed from this pathway could be retrofitted to achieve near-zero CO_2 emissions. This technology pathway would reduce CO_2 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 CO_2 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

1 2 ③ 4 5 6 7 8 9 10

Low — High

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

Commercial Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- 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

1 2 ③ 4 5 6 7 8 9 10

Low — High

- 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

1 2 3 ④ 5 6 7 8 9 10

Low — High

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

Economic Risk

1 2 3 ④ 5 6 7 8 9 10

Low — High

- Some risk from foreign competition in international markets.

Regulatory Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- 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.

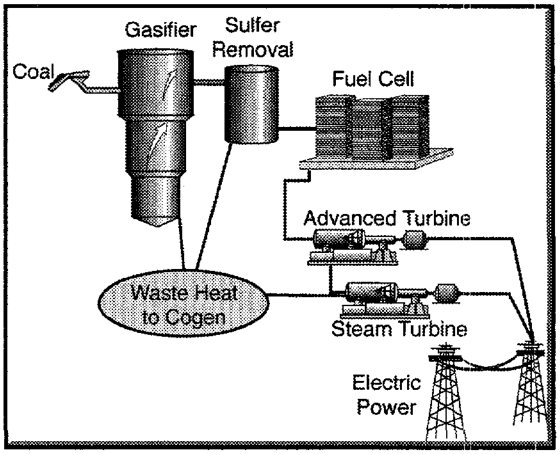
6.2 LOW-CARBON FUELS AND HIGH-EFFICIENCY POWER GENERATION

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 ATSs. This pathway also includes stand-alone applications of small to medium ATSs, including cogeneration. Near zero CO_2 emissions could be achieved with integration of CO_2 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 ATSs.
- 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 CO_2 capture technologies as they become available.



Representative Technologies

- ATSs
- High-temperature fuel cells
- Methane conversion
- Coal gasification, CO_2 capture

Technology Status/Applications

- ATSs (hydrogen and ultra-high-temperature), high-temperature fuel cells, and CO_2 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 CO_2 capture and other environmental controls need extensive development.
- ATSs 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 ATS program, achieving busbar energy costs that are 10% less than costs of current technology.
- Developing the ATS 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 CO_2 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 ATSs 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 ATS 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 CO_2 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 CO_2 emissions, pending development of cost-effective CO_2 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 CO_2 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 CO_2 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, CO_2 capture, and CO_2 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.

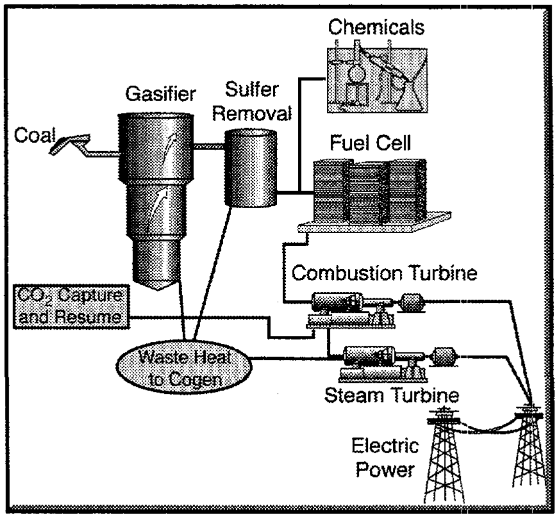
6.3 ULTRA-HIGH EFFICIENCY, ZERO-CARBON EMISSION ENERGYPLEXES

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 CO_2, 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 CO_2. 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 emissions to the environment, while producing a CO_2 stream.

RD&D Challenges

- Develop process concepts for power plants resulting in zero CO_2 release to the atmosphere.
- Produce hybrid coal and refinery plants to produce fuels, electricity, and chemicals with less CO_2 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 CO_2 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

1 2 3 4 ⑤ 6 7 8 9 10
Low — High

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

Commercial Risk

1 2 3 4 ⑤ 6 7 8 9 10
Low — High

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

Ecological Risk

1 ② 3 4 5 6 7 8 9 10
Low — High

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

Human Health Risk

1 2 ③ 4 5 6 7 8 9 10
Low — High

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

Economic Risk

1 2 3 4 5 ⑥ 7 8 9 10
Low — High

- Public would support extra-low emisisons approach.

Regulatory Risk

1 2 3 ④ 5 6 7 8 9 10
Low — High

- Regulatory risk for coal systems is moderate, due to CO_2 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.