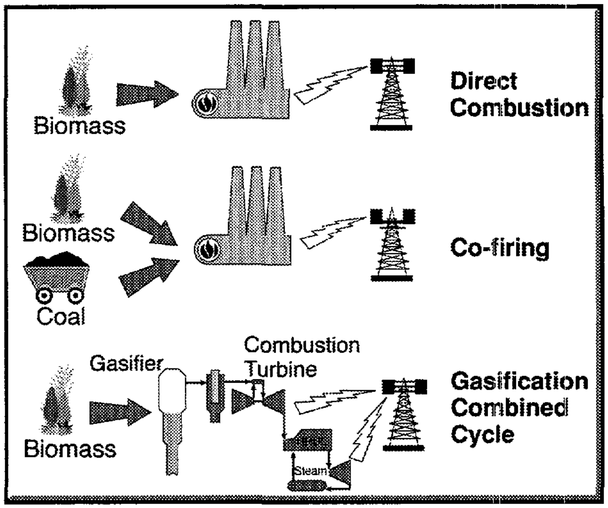
Clean Energy Technologies

8. Renewable Energy

8.1 BIOMASS ELECTRIC

Technology Description

Biomass electric, also called biomass power or biopower, is the generation of electric power from biomass resources ranging from agricultural and forest product residues to crops grown specifically for energy production. Biopower reduces GHG emission by substituting biomass for coal in existing power plants or using biomass alone in plants that displace new fossil plants. Since biomass absorbs CO_2 as it grows, the entire biopower process of growing, burning, and regrowing biomass can result in very low CO_2 emissions, depending on the amount of fossil fuel used for fertilization, cultivation, transportation, and so on.



System Concepts

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

Representative Technologies

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

Technology Status/Applications

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

Current Research, Development, and Demonstration

RD&D Goals

By 2005:

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

By 2010:

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

By 2020:

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

RD&D Challenges

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

RD&D Activities

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

Recent Success

- Identifying the fouling mechanisms in commercial combustion equipment provided a way to mitigate the problem and has resulted in innovative approaches to alternative combustion technologies. One approach is applying ceramic filter elements to the hot-gas cleaning process for high-pressure air gasification; it is currently in long-term testing.

Commercialization and Deployment

- Biopower capacity in the United States is 10 GW; ~2/3 is grid-connected, and the remaining facilities offset power purchases. Capacity in the rest of the world is about 20–25 GW. U.S. investment in equipment is $300M to $500M/year. At least six major engineering procurement and construction companies and several multinational boiler manufacturers are active. Competing technologies include low-cost subsidized fuels abroad and biomass technologies developed in Scandinavia. Guarantees and warranties are a significant issue, giving established technologies an advantage despite their lower efficiency and higher carbon emissions compared with advanced IGCC and other advanced modular technologies. The critical challenge to widespread deployment is cost and reliability of the fuel supply, especially outside industries such as sugar and pulp and paper. Lack of well-demonstrated performance of advanced technologies continues to be a barrier to implementation.

Potential Benefits and Costs

Carbon Reductions

- 2010: 10–20 MtC/year; 2020: 15–25 MtC/year; 2030: 25–40 MtC/year (not including landfill gas).
- This assumes significant RD&D investment in crop and infrastructure development, optimizing cofiring benefits and costs, and demonstrating gasification-based technologies.
- It is assumed that cofiring will directly replace coal power generation and gasification systems will replace the average power system carbon emissions.

RD&D Expenditures

- DOE Biomass Power Program funding: ~$24M in FY 1996 and $26M in FY 1997; no other significant federal funding. U.S. funding including the private sector: ~$36M. The largest non-U.S. effort is within the European Union. Total public and private investment in R&D is about $50M.
- Estimated federal funding required to achieve the target market penetrations is $69M/year in 2000–2010, $87M/year in 2010–2020, and $127M/year in 2020–2030.

Market

- The estimated cofiring cumulative capacity is 5750 MW in 2010 and beyond, including 400 MW of existing capacity. The estimated direct combustion capacity is about 7000 MW currently, 8250 in 2010, 8650 in 2020, and 9100 in 2030. The estimated IGCC capacity is 1,950 in 2010, 7,100 in 2020, and 16,350 in 2030.

Nonenergy Benefits and Costs

- Rural economic development due to employment in feedstock production and transportation. Major export potential (cumulative 3 trillion kWh demand growth in non-OECD Asia through 2010); potential job reductions in mining industry.

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Cofiring and direct combustion systems are lower; IGCC with residues and energy crop development are higher.

Commercial Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Cofiring is lower and feedstock development is higher.

Ecological Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Conversion system risk is low; dedicated feedstock production depends on other land uses displaced.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- Risks are mainly from particulate and other emissions from power plants, plus feedstock production and transportation.

Economic Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Positive employment impact, requires less subsidy than many other renewables, develops technology for export markets.

Regulatory Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Number reflects the overall risk associated with utility regulation/deregulation, as well as farm policy. Risks comparable to those for other electricity generating technologies.

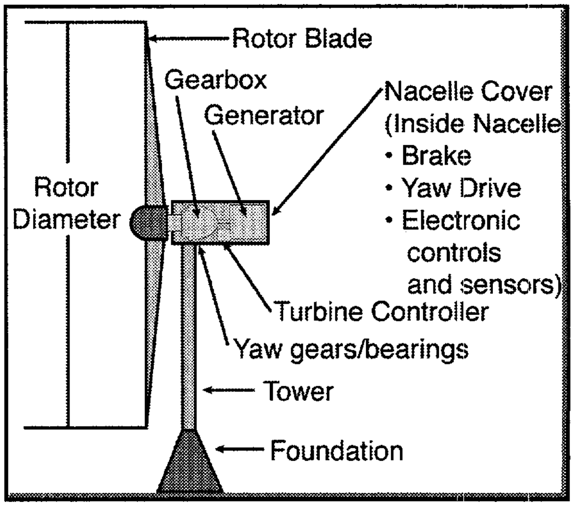
Key Federal Actions

- Continued funding of RD&D in biopower and feedstock areas as outlined
- Regulatory reforms: DFSS to be classified as agricultural for tax purposes
- Codes and standards: address standards activities for both biomass feedstock trade and the beneficial use of ash
- Federal procurement—in the area of modular systems—for its land management and defense arena, plus significant demonstration activities
- R&D activities in progressively more advanced conversion technologies (e.g., fuel cells and hybrid cycles).

8.2 WIND ENERGY

Technology Description

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



System Concepts

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

Representative Technologies

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

Technology Status/Applications

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

Current Research, Development, and Demonstration

RD&D Goals

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

RD&D Challenges

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

RD&D Activities

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

Recent Success

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

Commercialization and Deployment

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

Potential Benefits and Costs

Carbon Reductions

- Wind energy produces zero carbon emissions per kilowatt hour.
- Wind energy without additional storage can reduce GHG emissions through displacing coal- and natural gas-fired power plants.

2010: 3–6 MtC/year; 2020: 15–30 MtC/year; 2030: 30–45 MtC/year

RD&D Expenditures

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

Market

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

Nonenergy Benefits and Costs

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

Risk Factors

Technical Risk

1 2 3 [✓ 4] 5 6 7 8 9 10

Low High

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

Commercial Risk

1 2 3 [✓ 4] 5 6 7 8 9 10

Low High

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

Ecological Risk

1 [✓ 2] 3 4 5 6 7 8 9 10

Low High

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

Human Health Risk

[✓ 1] 2 3 4 5 6 7 8 9 10

Low High

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

Economic Risk

1 2 [✓ 3] 4 5 6 7 8 9 10

Low High

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

Regulatory Risk

1 2 3 [✓ 4] 5 6 7 8 9 10

Low High

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

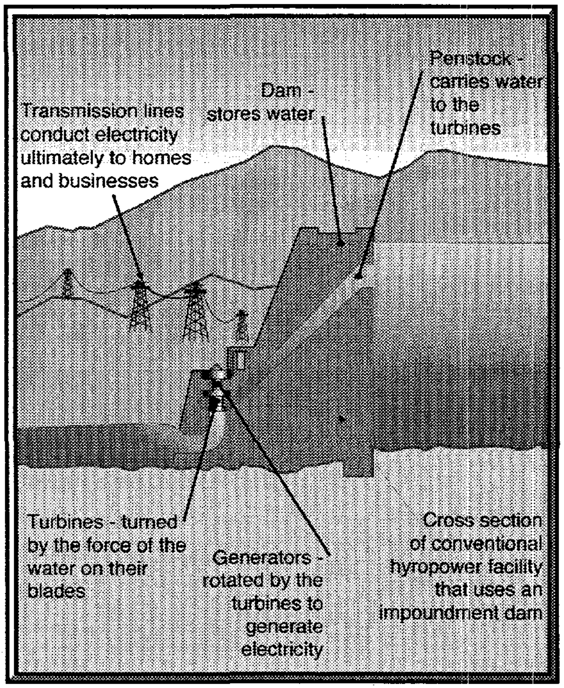
Key Federal Actions

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

8.3 ADVANCED HYDROPOWER

Technology Description

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



System Concepts

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

Representative Technologies

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

Technology Status/Applications

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

Current Research, Development, and Demonstration

RD&D Goals

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

RD&D Challenges

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

RD&D Activities

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

Recent Success

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

Commercialization and Deployment

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

Potential Benefits and Costs

Carbon Reductions

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

RD&D Expenditures

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

Market

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

Nonenergy Benefits and Costs

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

Risk Factors

Technical Risk

1 ② 3 4 5 6 7 8 9 10
Low High

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

Commercial Risk

1 2 3 ④ 5 6 7 8 9 10
Low High

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

Ecological Risk

1 ② 3 4 5 6 7 8 9 10
Low High

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

Human Health Risk

1 ② 3 4 5 6 7 8 9 10
Low High

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

Economic Risk

1 2 3 ④ 5 6 7 8 9 10
Low High

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

Regulatory Risk

1 2 3 ④ 5 6 7 8 9 10
Low High

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

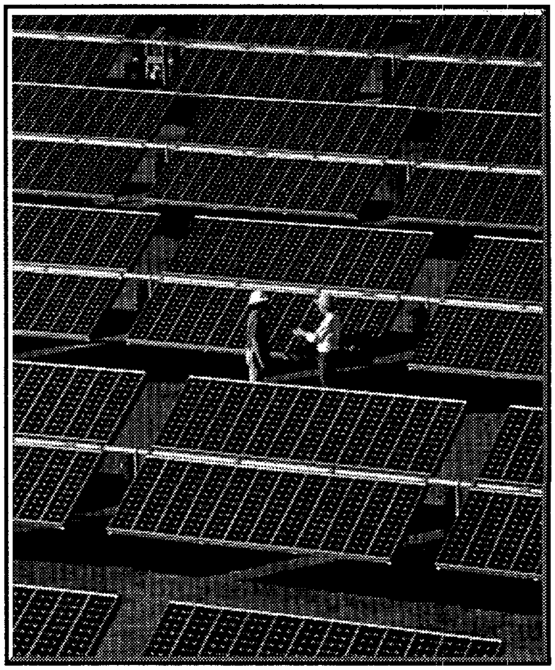
Key Federal Actions

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

8.4 SOLAR PHOTOVOLTAICS

Technology Description

Photovoltaic (PV) devices convert sunlight to electricity without moving parts and without producing fuel wastes, air pollution, or GHGs. A PV-generating station 140 km by 140 km in area at an average solar site in the United States could generate all of the electricity needed in the country (2.5×10^6 GWh/year), assuming a system efficiency of 10% and an area packing factor of 50% (to avoid self-shading). A well-planned transition to solar PV for electricity and transportation could make serious inroads in reducing CO_2.



System Concepts

- Flat-plate PV arrays use global sunlight; concentrators use direct sunlight. Modules are mounted on a stationary array or on single- or dual-axis sun trackers. Arrays can be ground-mounted or on all types of buildings and structures. PV dc output can be conditioned into grid-quality ac electricity, or dc can be used to charge batteries or to split water to produce H_2.
- PV systems are expected to be used in the United States for residential and commercial buildings, peak power shaving, and intermediate daytime load following; with electric storage and improved transmission, systems could be used for dispatchable electricity and H_2 production in the future.
- Most locations in the United States and worldwide have enough sunlight to make PV useful locally.

Representative Technologies and Status

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

Current Research, Development, and Demonstration

RD&D Challenges and Goals

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

RD&D Activities

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

Recent Successes

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

Commercialization and Deployment

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

Potential Benefits and Costs

Carbon Reductions

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

RD&D Expenditures

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

Markets

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

Nonenergy Benefits and Costs

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

Risk Factors

Technical Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

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

Commercial Risk

1 2 3 4 5 ⑥ 7 8 9 10

Low High

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

Ecological Risk

1 ② 3 4 5 6 7 8 9 10

Low High

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

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

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

Economic Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

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

Regulatory Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

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

Key Federal Actions

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

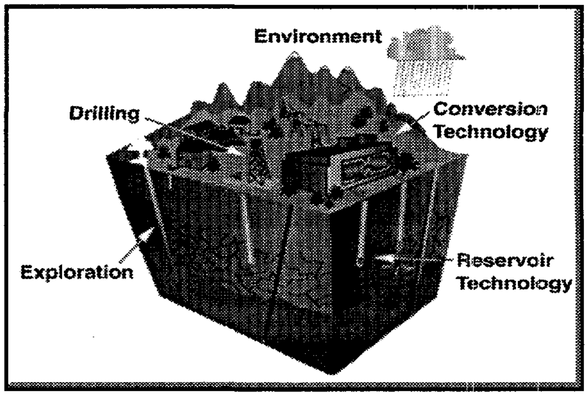
8.5 GEOTHERMAL ENERGY

Technology Description

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

System Concepts

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



Representative Technologies

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

Technology Status/Applications

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

Current Research, Development, and Demonstration

RD&D Goals

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

RD&D Challenges

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

RD&D Activities

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

Recent Success

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

Commercialization and Deployment

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

Commercialization and Deployment (continued)

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

Potential Benefits and Costs

Carbon Reductions

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

RD&D Expenditures

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

Market

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

Nonenergy Benefits and Costs

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

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

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

Commercial Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

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

Ecological Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

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

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

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

Economic Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

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

Regulatory Risk

1 ② 3 4 5 6 7 8 9 10

Low High

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

Key Federal Actions

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

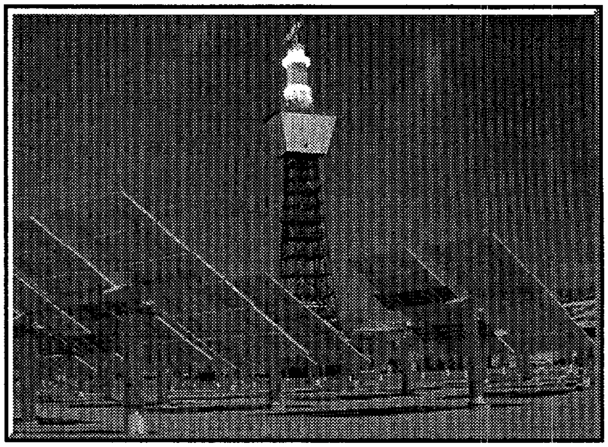
8.6 SOLAR THERMAL ELECTRIC AND BUILDINGS

Technology Description

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

System Concepts

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



Representative Technologies

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

Technology Status/Applications

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

Current Research, Development, and Demonstration

RD&D Goals

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

RD&D Challenges

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

RD&D Activities

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

Recent Success

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

Commercialization and Deployment

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

Potential Benefits and Costs

Carbon Reductions

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

RD&D Expenditures

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

Market

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

Nonenergy Benefits and Costs

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

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

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

Commercial Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

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

Ecological Risk

1 ② 3 4 5 6 7 8 9 10

Low High

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

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

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

Economic Risk

1 2 3 4 5 ⑥ 7 8 9 10

Low High

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

Regulatory Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

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

Key Federal Actions

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

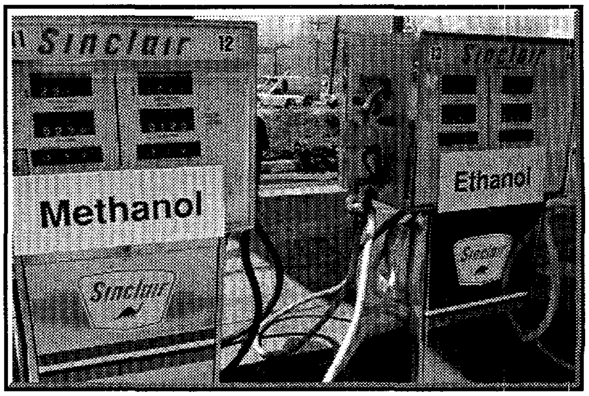
8.7 BIOMASS TRANSPORTATION FUELS

Technology Description

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

System Concepts

- Biomass for conversion to liquid fuels can be obtained from wastes, grass, or tree crops grown for energy production, and coproduction and harvesting of biomass feedstocks with other plant products. Growth of microalgae using CO_2 from fossil fuel combustion is also a potentially large feedstock for fuel production.
- The waste products from manufacturing biofuels (mainly lignin) can be used to generate electricity; enough electricity can be generated to power the plant and return an equal amount to the grid.



Representative Technologies

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

Technology Status/Applications

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

Current Research, Development, and Demonstration

RD&D Goals

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

RD&D Challenges

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

RD&D Activities

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

Recent Success

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

Commercialization and Deployment

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

Potential Benefits and Costs

Carbon Reductions

- The CO_2 released when biofuels are used is recycled by plants, resulting in net carbon emissions approaching zero; displacing a unit of energy from gasoline with a unit of energy from ethanol in light-duty vehicles results in a 90% reduction in carbon emissions. Similar reductions can be expected from such biomass fuels as methanol, biodiesel, and other biofuels. Although there are several potential different biofuels, carbon reduction estimates were made only on ethanol using switchgrass as a feedstock at 10% and 95% blends, compared with reformulated gasoline. Carbon reduction estimates assume a market penetration for these blends of 4 billion gal in 2010, 9.5 billion gal in 2020, and 9.5 billion gal in 2030. With the low projected price of gasoline, and without extra policy incentives, neat ethanol was not considered cost-effective enough to use as a transportation fuel during this 30-year period. Calculations included carbon reductions from biomass-generated electricity returned to the grid from ethanol plants.
- Carbon reductions were estimated as 5–15 MtC/year in 2010, 20–30 MtC/year in 2020, and 20–35 MtC/year in 2030.
- **RD&D Expenditures**
- Funding of around $23M/year has been spent in FY 1996 and FY 1997, supporting research by national laboratories, universities, and industry partners.
- Achieving the economical carbon reduction costs described above requires significant funding increases. The technology improvements required call for quickly ramping up the research program from its current level, averaging $75M/year during 2000–2010. During 2010–2020, an average of $100M/year would be needed for work on biomass production to ensure a large and cost-effective resource base for fuel production by 2020. Fuel production technologies must close the cost gap between petroleum and biomass-derived fuels. During 2020–2030, $50M/year would be required.

Market

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

Nonenergy Benefits and Costs

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

Risk Factors

Technical Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

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

Commercial Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

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

Ecological Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

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

Human Health Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

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

Economic Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Only modest investments in infrastructure are needed.

Regulatory Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

Key Federal Actions

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

8.8 SOLAR ADVANCED PHOTOCONVERSION

Technology Description

Photoconversion technology encompasses sunlight-driven quantum-conversion processes (other than solid-state PVs) that lead to the direct and potentially highly efficient production of fuels, materials, chemicals, and electrical power from simple renewable substrates such as water, CO_2, and molecular nitrogen. This technology has the potential to eliminate the need for fossil fuels by substituting renewable sources and conversion processes that are either carbon neutral (any carbon generated is reused during plant growth) or carbon free (e.g., hydrogen from water). These technologies also can convert CO_2 into liquid and gaseous fuels via processes that are often termed biomimetic or artificial photosynthesis.

System Concepts

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

Representative Technologies

- Elements of this future solar technology include photobiological, photochemical, photoelectrochemical, photocatalytic, and dark catalytic processes for energy production.
- Photoconversion technologies can result in electrical power production; hydrogen production and utilization; biodiesel, organic acid, methane, and methanol production; bioplastics; the removal of CO_2 from the atmosphere as a consequence of photoreduction of CO_2 to fuels, materials, and chemicals production; atmospheric nitrogen fixation (independent of natural gas); and waste or biomass utilization upon photoconversion to fuels, materials, or chemicals. Most of these technologies are at early stages of research, but some are at the development level, and a couple are commercial (those that produce high-value products).

Technology Status/Applications

- Power production: dye-sensitized, nanocrystalline, titanium dioxide semiconductor solar cells are at the 8–11% efficiency level and are potentially very cheap. In contrast to solid-state PV solar cells, light is absorbed by dye molecules in contact with a liquid rather than solid-state semiconductor materials. Novel photoelectrochemical cells with integrated fuel cells and in situ storage for 24-h solar power have been demonstrated at 6–7% efficiency in 4 × 8 ft panels (Texas Instruments system), and photochargeable batteries that include electrochemical storage have been demonstrated with 24-h power output. Hot-carrier photoconversion technology for increasing solar conversion efficiencies (theoretical efficiency limits of 65%) is making progress. The term "hot carrier" refers to electrons initially excited by light, when they have energy higher than their equilibrium levels. This excess energy is given off in the first fraction of a second as heat, and hot-carrier technology attempts to capture this lost heat as useful electricity.
- Fuels production: Photoelectrochemical and photobiological processes that will lead to hydrogen production from water or gasified biomass are at the early stages of research and making good progress; biodiesel, methane, and methanol production from water, waste, and CO_2 are at various stages of R&D; and fuels, such as methanol, produced by the direct electrocatalytic or photocatalytic reduction of CO_2, are at the early fundamental research stage. Electrocatalytic concentration of CO_2 from the atmosphere is being studied as well; it is of interest to persons involved in atmospheric controls in small spaces (i.e., submarines) and has potential for removing CO_2 from the atmosphere in the future.
- Materials and chemicals production: producing materials and chemicals from CO_2 and/or biomass will reduce CO_2 emissions compared with the fossil fuels used currently.
- Photobiological production of pigments (e.g., astaxanthin), health foods, nutritional supplements (e.g., omega-3 fatty acids), protein, and fish food is commercial. Production of biopesticides and pharmaceuticals is under development. Production of commodity chemicals such as, but not limited to, glycerol, hydrogen peroxide, and bioemulsifiers is possible. Photocatalytic production of specialty or high-value chemicals has been demonstrated.

Current Research, Development, and Demonstration

RD&D Goals

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

RD&D Challenges

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

RD&D Activities

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

Recent Success

- Dye-sensitized nanocrystalline semiconductor solar cells have been demonstrated as power sources in small niche markets. Commercial interest is very high since they also can be configured to produce hydrogen.
- Scientific breakthroughs over the past 5 years have been made in microbial and enzymatic R&D, natural photosynthesis, semiconductor nanostructure and superlattice understanding, CO_2 catalysis, and energy and electron transfer in artificial donor/acceptor molecules.

Commercialization and Deployment

- Large-scale algal ponds are producing high-value chemicals on a commercial basis using photobiological processes. As an example, the current astaxanthin market is $180M per year and will rise to $1B in 5 years. Astaxanthin, a pigment synthesized from petroleum, is used as a coloring agent in the poultry and salmon industries. Algal production of the pigment just started in Hawaii and is replacing the fossil version for health and environmental reasons.
- SMH Corporation (a European company) has just started to sell dye-sensitized, nanocrystalline cell-powered watches. The market is estimated to be 100 million units.

Potential Benefits and Costs

Carbon Reductions

- Photoconversion processes can ultimately replace (or displace) all fossil fuels as a source of energy, materials, and chemicals. The time scale is uncertain, but significant impacts on reduction of CO_2 release could begin in the next 30 to 50 years. It should be emphasized that solar photoconversion produces no CO_2 and can in fact remove CO_2 from the atmosphere.

RD&D Expenditures

- A significant level of basic research activities in solar photoconversion is currently being funded by ER (BES—chemical sciences, material sciences, and energy biosciences) (estimated level: $10–15M); some exploratory R&D is being funded by EE PV (estimated $400K).
- Some basic research support by NSF and USDA is complementary.
- Federal R&D expenditures must be at a sufficient level to fund critical-mass groups to address fundamental problems in key areas, and the support must be consistent over the next 20–30 years to ensure successful R&D efforts. Suggested levels are a minimum of $50M/year for improvements that will help reduce carbon emissions; substantially higher levels will be required to reap benefits that are outside of the scope of a budget driven by carbon reductions. Also, additional funds will be required for applied and production research for technology thrusts that prove worthy of commercialization; given the fundamental nature of the current research, it is not possible at this time to estimate what those requirements might be.

Market

- Photoconversion processes have the potential to replace all fossil sources for power, fuel, materials, and chemicals production.

Nonenergy Benefits and Costs

- Many spin-off technologies are possible. These include opto-electronics, biosensors, biocomputers, bioelectronics, and nano-scale devices.

Risk Factors

Technical Risk

1 2 3 4 5 6 ⑦ 8 9 10
Low High

- Most photoconversion research is high risk, high payoff.

Commercial Risk

1 2 3 4 5 ⑥ 7 8 9 10
Low High

- Initial commercial success in the biological area and solar cell supports the prospects for high payoff of this direction of R&D.

Ecological Risk

1 2 ③ 4 5 6 7 8 9 10
Low High

- While technologies are still in the early stages of development, ecological risk should be low.

Human Health Risk

1 2 ③ 4 5 6 7 8 9 10
Low High

- While technologies are still in the early stages of development, human health risk should be low.

Economic Risk

1 2 3 4 5 ⑥ 7 8 9 10
Low High

- Economic risk will decrease with time and research investment.

Regulatory Risk

1 2 3 4 5 6 7 8 9 10
Low High

- Not applicable. Lower than for current fossil technologies.

Key Federal Actions

- Federal R&D support enhances the scientific and technology base at the fundamental level where risk is too great for private sector support.
- The critical factor for success is critical-mass support for a sufficient period of time to develop key understanding and technology without large fluctuations in research funding.