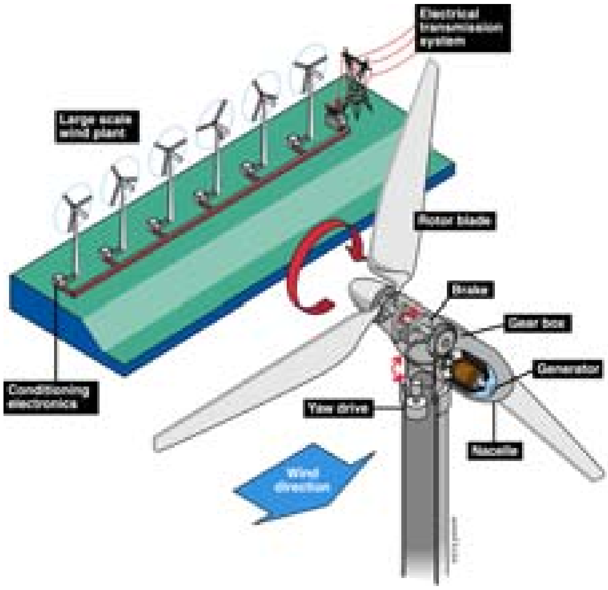
2.3 RENEWABLE ENERGY AND FUELS

2.3.1 WIND ENERGY

Technology Description



Wind turbine technology converts the kinetic energy in wind to electricity. Grid-connected wind power reduces greenhouse gas 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 in developing countries.

System Concepts

- Most modern wind turbines operate using aerodynamic lift generated by airfoil-type blades, yielding much higher efficiency than traditional windmills that relied on wind "pushing" the blades. Lifting forces spin the blades, driving a generator that produces electric power in proportion to wind speed. Turbines either rotate at constant speed and directly link to the grid, or at variable speed for better performance, using a power electronics system for grid connection. Utility-scale turbines for wind plants range in size up to several megawatts, and smaller turbines (under 100 kilowatts) serve a range of distributed, remote, and stand-alone power applications.

Representative Technologies

- The most common machine configuration is a three-bladed wind turbine, which operates "upwind" of the tower, with the blades facing into the wind. To improve the cost-effectiveness of wind turbines, technology advances are being made for rotors and controls, drive trains, towers, manufacturing methods, site-tailored designs, and offshore and onshore foundations.

Technology Status/Applications

- In the United States, the wind energy capacity tripled from 1,600 MW in 1994 to more than 6,700 MW by the end of 2004 – enough to serve more than 1.6 million households.
- Current performance is characterized by levelized costs of 4-6¢/kWh (depending on resource quality and financing terms), capacity factors of 30%-50%, availability of 95-98%, total installed costs of approximately \$800-\$1,100/kW, and efficiencies of 65%-75% of theoretical (Betz limit) maximum.

Current Research, Development, and Demonstration

RD&D Goals

- By 2007: For distributed wind turbines under 100 kw, achieve a power production cost of 10-15¢/kWh in Class 3 winds.
- By 2012: For larger systems greater than 100 kw, the goal is to achieve a power production cost of 3¢/kWh for onshore at sites with average wind speeds of 13 mph (wind Class 4), and 5¢/kWh at offshore sites with average wind speeds of 13 mph (wind Class 4).

RD&D Challenges

- Developing wind technology that will be economically competitive at low (13 mph) wind-speed sites requires optimizing increasingly large turbine designs in a fatigue-driven environment with minimal or no component replacements, requiring improved knowledge of wind inflow, aerodynamics, structural dynamics and materials, and optimal control of turbines and wind farms.
- Developing information and strategies to facilitate and optimize integration of wind power into electric grid systems.
- Developing offshore wind technology to take advantage of the immense wind resources in shallow and deep waters of U.S. coastal areas and the Great Lakes near large energy markets.
- Conducting analysis and R&D to explore the role of wind power in the production of hydrogen, in both large-scale and distributed systems.

RD&D Activities

- Core and university research: wind characteristics and forecasting, aerodynamics, structural dynamics and fatigue, and control systems for turbines and wind farms.
- Turbine research: cost-shared design and testing of next-generation utility-grade technology for low wind-speed sites, performance verification of onshore and offshore prototypes, development of advanced small turbines for distributed power applications, and component and system testing at the National Wind Technology Center (NWTC).
- Cooperative research and testing: collection of wind turbine-performance data, power-systems integration, resource assessment, industry technical support, participation in international standards development, wind turbine-certification assistance, and regionally targeted outreach.

Recent Progress

- In 1989, the wind program set a goal of 5¢/kWh by 1995 and 4¢/kWh by 2000 for sites with average wind speeds of 16 mph. The program and the wind industry met the goals as part of dramatic cost reductions from 25¢-50¢/kWh in the early 1980s to 4¢-6¢/kWh today
- Wind power is the world's fastest-growing energy source. In the past decade, the global wind energy capacity has increased ten fold from 3,500 MW in 1994 to almost 50,000 MW by the end of 2004. During 2004, nearly 8,000 MW of new capacity was added worldwide.
- Domestic public interest in environmentally responsible electric generation technology is reflected by new state energy policies and in the success of "green marketing" of wind power throughout the country.
- 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 – such as blade structural test stands and a large gearbox test stand – not otherwise available to the domestic industry.

Commercialization and Deployment Activities

- Installed wind capacity in the United States expanded from 2,554 MW to 6,740 MW during the period of 2000 to 2004.
- California has the greatest installed wind capacity, followed by Texas, Iowa, Minnesota, Oregon, Washington, Wyoming, New Mexico, Colorado, and Oklahoma.
- Wind technology is competitive today in bulk power markets with support from the production tax credit – and in high-value niche applications or markets that recognize non-cost attributes. Its competitiveness is affected by policies regarding ancillary services and transmission and distribution regulations. Continued

cost reductions from low wind-speed technologies will increase the resource areas available for wind development by 20-fold and move wind generation five times closer to major load centers.

- The principal markets for wind energy are substitution for new natural gas combined-cycle plants or displacement of fuel from existing plants, and replacement of coal-generated power plants. Emerging markets for wind energy include providing energy for water purification, irrigation, and hydrogen production.
- 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 such as wind energy.
- In the United States, the wind industry is thinly capitalized, except for General Electric Wind Energy, which recently acquired wind technology and manufacturing assets in April 2002. About six manufacturers and six to 10 developers characterize the U.S. industry.
- In Europe, there are about 10 turbine manufacturers and about 20 to 30 project developers. European manufacturers have established North American manufacturing facilities and are actively participating in the U.S. market.

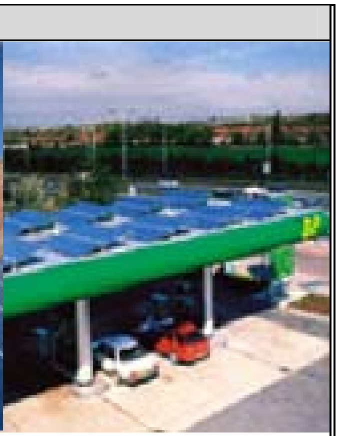
- Initial lower levels of wind deployment (up to 15%-20% of the total U.S. electric system capacity) are not expected to introduce significant grid reliability issues. Since the wind resource is variable, intensive use of this technology at larger penetrations may require modification to system operations or ancillary services. Transmission infrastructure upgrades and expansion will be required for large penetrations of onshore wind turbines. However, offshore resources are located close to major load centers.
- Small wind turbines (100 kW and smaller) for distributed and residential grid-connected applications are being used to harness the Nation’s abundant wind resources and defer impacts to the long-distance transmission market. Key market drivers include state renewable portfolio standards, incentive programs, and demand for community-owned wind applications.

2.3.2 SOLAR PHOTOVOLTAIC POWER

Technology Description


Semi-transparent PV canopy


PV solar arrays for larger-scale electricity.


PV panels on rooftop.

Solar photovoltaic (PV) arrays use semiconductor devices called solar cells to convert sunlight to electricity without moving parts and without producing fuel wastes, air pollution, or greenhouse gases. Using solar PV for electricity – and eventually using solar PV to produce hydrogen for fuel cells for electric vehicles or by producing hydrogen from water – will help reduce carbon dioxide emissions worldwide.

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 (e.g., see semi-transparent solar canopy, right). The DC output from PV can be conditioned into grid-quality AC electricity, or DC can be used to charge batteries or to split water to produce hydrogen (electrolysis of water).
- 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 energy storage, PV can provide dispatchable electricity and/or produce hydrogen.
- Almost all locations in the United States and worldwide have enough sunlight for cost-effective PV. For example, U.S. sunlight in the contiguous states varies by only about 25% from an average in Kansas. Land area is not a problem for PV. Not only can PV be more easily sited in a distributed fashion than almost all alternatives (for example, on roofs or above parking lots), a PV-generating station 140 km by 140 km sited at a high solar insolation location in the United States (such as the desert Southwest) 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).

Representative Technologies and Status

- Wafers of single-crystal or polycrystalline silicon – best cells: 25% efficiency; commercial modules: 13%-17%. Silicon modules dominate the PV market and currently cost about \$2/W_p to manufacture.
- Thin-film semiconductors (e.g., amorphous silicon, copper indium diselenide, cadmium telluride, and dye-sensitized cells) – best cells: 12%-19%; commercial modules: 6%-11%. A new generation of thin-film PV modules is going through the high-risk transition to first-time and large-scale manufacturing. If successful, market share could increase rapidly.
- High-efficiency, single-crystal silicon and multijunction gallium-arsenide-alloy cells for concentrators – best cells: 25%-37% efficient; commercial modules: 15%-24%; prototype systems are being tested in high solar areas in the southwest United States.
- Grid-connected PV systems currently sell for about \$6-\$7/W_p (17¢-22¢/kWh), including support structures, power conditioning, and land.

Current Research, Development, and Demonstration

RD&D Goals

- Overall research goals include scaling up laboratory-sized PV cells to much larger sizes suitable for product markets; validation of new module technologies for outdoors use to achieve 30-year outdoor warrantable lifetimes; and addressing of substantial technical issues associated with high-yield, first-time, and large-scale (greater than 100 MW/yr) manufacturing for advanced technologies.
- The long-term cost goal for electricity from PV cells for residential PV applications is $0.06/kWh, compared to costs ranging from $0.18 to $0.23/kWh in 2004.
- The interim cost goal is to reduce the 30-year user cost for PV electric energy to a range of $0.14 to $0.19/kWh by 2010.

RD&D Challenges

- Improve fundamental understanding of materials, processes, and devices to provide a technology base for advanced PV options.
- Improve and invent new low-cost processes and technologies; reduce module and balance-of-systems manufacturing costs.
- Develop and validate new, lower-cost systems hardware and integrated applications.

RD&D Activities

- Capabilities at national labs and university centers of excellence have been developed, both in expertise and unique facilities. Funding is split 50-50 between national labs and external subcontracts with universities and industry. Public/private R&D partnerships, including extensive national R&D teams, have been the favored approach. All subcontracts have been awarded via competitive solicitations to select the best and most committed research partners.
- DOE and the National Center for Photovoltaics have worked with state regulatory agencies and influenced the direction of state programs.
- The Department of Defense (DOD) has some funding through special programs in which PV has a role supplying power for military systems.
- The National Aeronautics and Space Administration (NASA) has some research funds for PV. Though this effort has decreased during the past decade, advanced PV has become very important for space missions (e.g., the high-performance cells on the Sojourner probe on Mars).
- Japan and Europe have significant funding for PV research.
- States have individual subsidy and utility portfolio programs related to PV; for example, California has a buy-down program for residential and commercial PV systems.
- U.S. PV businesses are marginally or not yet profitable and are unable to fund their own advanced research for low-cost PV.

Recent Progress

- Because of public/private partnerships, such as the Thin-Film Partnership with its national research teams, U.S. PV technology leads the world in measurable results such as record efficiencies for cells and modules. Another partnership, the PV Advanced Manufacturing R&D program, has resulted in industry cost reductions of more than 60% and facilitated a sixteen-fold increase of manufacturing capacity during the past 12 years.
- A new generation of potentially lower-cost technologies (thin films) is entering the marketplace. A 25-megawatt amorphous silicon thin-film plant by United Solar is reaching full production in 2005. Two plants (First Solar and Shell Solar) using even newer thin films (cadmium telluride and copper indium diselenide alloys) are in first-time manufacturing at the MW-scale. Thin-film PV has been a focus of the Federal R&D efforts of the past decade because it holds considerable promise for module cost reductions.
- During the past two years, record sunlight-to-electricity conversion efficiencies for solar cells were set by Federally funded universities, national labs, or industry in copper indium gallium diselenide (19%-efficient cells and 13%-efficient modules) and cadmium telluride (16%-efficient cells and 11%-efficient modules). Cell and module efficiencies for these technologies have increased more than 50% in the past decade.

- A unique multijunction gallium-arsenide-alloy cell was spun off to the space power industry, leading to a record cell efficiency (35%) and an R&D 100 Award in 2001. This device configuration is expected to dominate future space power for commercial and military satellites. Recent champion cell efficiency has reached 37% under concentrated sunlight. DOE is interested in this technology (III-V multijunctions), as an insertion candidate for high efficiency terrestrial PV concentrator systems.

Commercialization and Deployment Activities

- Worldwide, approximately 1,200 MW of PV were sold in 2004, with systems valued at more than $7 billion; total installed PV is more than 2 GW. The U.S. world market share fell to about 12% in 2004.
- Worldwide, market growth for PV has averaged 25%/year for the past decade as a result of reduced prices and successful global marketing. Worldwide sales grew 36% in 2001, 44% in 2002, 33% in 2003, and 60% in 2004.
- Hundreds of applications are cost effective for off-grid needs. However, the fastest growing segment of the market is grid-connected PV, such as roof-mounted arrays on homes and commercial buildings in the United States. California is subsidizing PV systems to reduce their dependence on natural gas, especially for peak daytime loads which match PV output, such as air-conditioning.

Market Context

- Electricity for remote locations, especially 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 daytime uses.
- Future electricity and hydrogen storage for dispatchable electricity, electric car-charging stations, and hydrogen production for portable fuel.

2.3.3 SOLAR HEATING AND LIGHTING

Technology Description

Solar heating and lighting technologies being developed for buildings applications include solar water heating and hybrid solar lighting.

System Concepts

- In solar heating systems, solar-thermal collectors convert solar energy into heat, usually for domestic hot water, pools, and space heating.
- In solar lighting systems, sunlight is transmitted into the interior of buildings using glazed apertures, light pipes, and/or optical fibers.

Representative Technologies

- Active solar heating systems use pumps and controls to circulate a heat-transfer fluid between the solar collector(s) and storage. System sizes can range from 1 to 100 kW.
- Passive solar heating systems do not use pumps and controls but rather rely on natural circulation to transfer heat into storage. System sizes can range from 1 to 10 kW.
- Transpired solar collectors heat ventilation air for industrial and commercial building applications. A transpired collector is a thin sheet of perforated metal that absorbs solar radiation and heats fresh air drawn through its perforations.
- Hybrid solar lighting systems focus concentrated sunlight on optical fibers and, with a controller, combine natural daylight with conventional illumination, depending on sunlight availability.

Technology Status/Applications

- Typical residential solar systems use glazed flat-plate collectors combined with storage tanks to provide 40%-70% of residential water heating requirements. Typical systems generate hot water equivalent to supplying 2,500 kWh/year at a cost of about 8¢/kWh.
- Typical solar pool heating systems use unglazed polymer collectors to provide 50%-100% of residential pool heating requirements. Typical systems generate 1,600 therms or 46,000 kWh/year and have 25% of the market.

Current Research, Development, and Demonstration

RD&D Goals

- Near-term solar water-heating research goals include use of polymer materials and manufacturing enhancements to reduce the cost of solar water heating systems to 4.5¢/kWh from their current cost of 8¢/kWh.
- Near-term solar-lighting research goals include demonstrating the second generation of the lighting system, coupled with an enhanced control system – and determining the market potential of the technology.

RD&D Challenges

- Solar heating RD&D efforts are targeted to reduce manufacturing and installation costs, improve durability and lifetime, and provide advanced designs for system integration. One key R&D issue is durability. Polymer materials in solar heating systems must survive harsh service environments that include exposure to elevated temperatures, moisture, and ultraviolet radiation.
- Demonstration of hybrid lighting-system performance and reliability in the field are critical to the success of solar lighting.

RD&D Activities

- Key DOE program activities are targeted to demonstrate lower cost and improved reliability of components and systems, develop advanced systems and applications, and support the next commercial opportunities for these technologies.
- DOE support of RD&D has been required because solar manufacturers are generally small businesses with limited resources and expertise. These manufacturers are constantly facing manufacturing and system design issues that affect the reliability, lifetime systems costs, and overall cost effectiveness of their products, yet they do not have the resources to conduct reliability and cost-reduction R&D. DOE and its national laboratories, however, have extensive expertise and facilities that can be critical to the long-term

success of these manufacturers.

Recent Progress

- More than 1,000 MW of solar buildings PV systems are operating successfully in the United States, generating more than 3 million MWh/year.
- The energy costs of solar-thermal systems have been reduced through technology improvements by more than 50%, saving more than 5 million MWh/yr in U.S. primary energy consumption.

Commercialization and Deployment Activities

- About 1.2 million solar water-heating systems have been installed in the United States. However, due to relatively low energy prices, there are currently only approximately 8,000 installations per year.
- Several hundred transpired solar collector systems have been installed, including installations for Ford Motor Company, General Motors, Federal Express, the U.S. Army, and the Bureau of Reclamation.

Market Context

- Retrofit markets: There are 73 million existing single-family homes in the United States. A potential replacement market of 29 million solar water-heating systems is based on the assumption that only 40% of the homes have been built with suitable orientation and absence of shading needed for solar water-heating systems.
- New construction markets: In 2000, 1.2 million new single-family homes were built in the United States. Assuming 70% of these homes could be sited to enable proper orientation of solar water-heating systems, new construction represents another 840,000 possible system installations each year.
- Solar building technologies will reduce daytime peak electricity requirements.

2.3.4 CONCENTRATING SOLAR POWER

Technology Description

Luz Trough Power Plant

Concentrating Solar Power (CSP) systems concentrate solar energy 50 to 5,000 times to produce high-temperature thermal energy, which is used to produce electricity for distributed or bulk generation process applications.

System Concepts

- In CSP systems, highly reflective sun-tracking mirrors produce temperatures of 400°C 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 solar-to-electric efficiencies for the system of up to 30%.
- CSP technologies provide firm, nonintermittent electricity generation (peaking or intermediate load capacity) when coupled with storage.
- Because solar-thermal technologies can yield extremely high temperatures, the technologies could some day be used for direct conversion (rather than indirect conversion through electrochemical reactions) of natural gas or water into hydrogen for future hydrogen-based economies.

Representative Technologies

- A parabolic trough system focuses solar energy on a linear 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 a fossil fuel to meet utility needs. Plant sizes can range from 1.0 to 100 MW_e.
- A power tower system 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 MW_e.
- A dish/engine system uses a dish-shaped reflector to power a small Stirling or Brayton engine/generator or a high-concentrator PV module mounted at the focus of the dish. Dishes are 2-25 kW in size and can be used individually or in small groups for distributed, remote, or village power; or in clusters (1-10 MW_e) for utility-scale applications, including end-of-line support. They are easily hybridized with fossil fuel.

Technology Status/Applications

- Nine parabolic trough plants, with a rated capacity of 354 MW_e, have been operating in California since the 1980s. Trough system electricity costs of about 12¢-14¢/kWh have been demonstrated commercially.
- Solar Two, a 10-MW_e pilot power tower with three hours of storage, provided all the information needed to scale up to a 30-100 MW commercial plant, the first of which is now being planned in Spain.
- A number of prototype dish/Stirling systems are currently operating in Nevada, Arizona, Colorado, and Spain. High levels of performance have been established; durability remains to be proven, although some systems have operated for more than 10,000 hours.

Current Research, Development, and Deployment

RD&D Goals

- The long-term goal is to achieve a power cost of between \$0.035/kWh and \$0.062/kWh, compared to the cost of between \$0.12-\$0.14/kWh in 2004.
- The interim goal is to reduce the cost of large-scale CSP power plants in the Southwest United States, where solar conditions are most favorable, to \$0.09-\$0.11/kWh by 2010.

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 the field are critical to the success of 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, and develop advanced systems and applications.
- Several European countries and Israel have programs comparable in size to the United States.
- DOE support of RD&D has been required because of the specialized technology development and the need for reducing costs and for reducing barriers to market penetration. The Federal CSP program provides expert technical support, as well as serving as a catalyst and facilitator for participation of utilities and manufacturers to assist in driving down system costs.

Recent Progress

- New commercial plants are being considered for California, Nevada, and Arizona.
- The 10-MW Solar Two pilot power tower plant operated successfully near Barstow, California, leading to the first commercial plant being planned in Spain.
- Operations and maintenance costs have been reduced through technology improvements at the commercial parabolic trough plants in California by 40%, saving plant operators $50 million.

Commercialization and Deployment Activities

- Parabolic troughs have been commercialized and nine plants (354 MW total) have operated in California since the 1980s.
- The state of Nevada announced plans to build a 50-MW parabolic trough plant near Boulder City. Nevada Power and Sierra Pacific Power will purchase the power to comply with the solar portion of Nevada’s renewable portfolio standard.
- Successful operation of Solar Two has provided the basis for a partnership to provide the first 30-100 MW power tower plant.
- The World Bank’s Solar Initiative is pursuing CSP technologies for less-developed countries. The World Bank considers CSP to be a primary candidate for Global Environment Facility funding, which could total $1-$2 billion for projects during the next two years.

Market Context

- There is currently 350 MW of CSP generation in the United States, all of it in Southern California's Mojave Desert.
- Power purchase agreements have been signed for 150 MW of new CSP capacity (50 MW in Nevada and 100 MW in Spain). The plants are anticipated to come on-line within the next two to three years. Significant domestic and international interest will likely result in additional projects.
- According to a recent study commissioned by the Department of Energy, CSP technologies can achieve significantly lower costs (below 4¢/kWh) at modest production volumes.
- Congress asked DOE to scope out what would be required to deploy 1,000MW of CSP in the Southwest United States. DOE is actively engaged with the western Governors to map a strategy to deploy 1-5 GW of CSP in the Southwest by 2015.
- A near-term to mid-term opportunity exists to build production capacity in the United States for both domestic use and international exports.

2.3.5 BIOCHEMICAL CONVERSION OF BIOMASS

Technology Description

Biomass resources are agricultural crops and residues, wood residues, grasses, and trees. Biomass absorbs CO_2 as it grows, offsetting the CO_2 emissions from harvesting and processing, and can be a substitute for fossil resources in the production of power, fuels, and chemicals. Biomass feedstocks currently supply about 3 quadrillion Btus (Quads) to the nation's energy supply, based primarily on the use of wood. The potential exists for increasing the total biomass contribution up to 10 Quads nationwide, which would have a positive impact on the farm economy. Cost, sustainable supply availability, biomass variability, and transportation systems are key challenges for biomass utilization. The use of biomass as an alternative to fossil resources reduces most emissions, including emissions of greenhouse gases (GHGs). Through the use of biomass materials that would otherwise go to waste, biomass systems can represent a net sink for GHG emissions because methane emissions that would result from landfilling the unused biomass would be avoided.

Sugars are important platform intermediates for producing fuels, products, and power from biomass. Technologies in manufacturing platforms – such as the sugars platform – can provide the basis for a biorefinery or be combined with those from other platforms. The sugars platform is used to break down biomass, cellulose, and hemicellulose polymers into their building blocks. The building blocks are sugars that can be converted to many products including liquid fuels (e.g., ethanol), monomeric components for the polymer market (e.g., lactic acid), and hydrogen. In addition to using sugar as a feedstock for fuel and chemical production, biomass rich in oils (such as soybean) can be converted to esters that are combusted like petroleum-based diesel. These oils have potential for the production of chemicals and other products, such as lubricants or polymers.

The biorefinery is analogous to an oil refinery. Multiple feedstocks are converted to a slate of products via multiple technology routes. Fuel production provides a large-volume product to achieve economies of scale, while lower-volume biobased coproducts and power can improve the economic competitiveness of biomass as a sustainable source of energy. Integrated biorefinery systems are being evaluated for their feasibility in producing fuels and products for potentially large commercial markets. A major challenge is to develop the ability to convert the fractionated biomass components into value-added products as efficiently as the current petrochemical business.

System Concepts

- The most common sugar-platform process consists of pretreating a biomass feedstock to release sugars from the fibrous cellulose and hemicellulose fractions. These sugars can be converted biologically into products such as ethanol or lactic acid, and can also be converted catalytically into products such as sorbitol. The products are then purified and sold as liquid fuels, sold into commodity chemical markets, or further converted and sold into other markets. The residue remaining from the sugar process can be burned to produce steam and electricity or further processed into other products such as animal feed.
- Oil technologies under development include conversion of glycerol to higher-value chemicals, including 1,3 propanediol.

Representative Technologies

- Sugar platform: hydrolysis of fibrous biomass that utilizes enzymes or acid catalysts, followed by microbial or catalytic conversion of the sugars to products.
- Glyceride platform: thermochemical transesterification of triglycerides.
- Fractionating biomass materials from grain and oil seeds, agricultural and forestry residues, or dedicated

biomass feedstocks (such as grasses and woody crops) into component parts allows further development of value-added products such as chemical intermediates, wood products, biodiesel fuel, and composite materials.

Technology Status/Applications

- Enzymatic hydrolysis: A major barrier of this sugar-platform technology has been development of low-cost cellulase enzyme cocktails. DOE has recently completed cost-shared subcontracts with Genencor International and Novozyme Biotech to reduce the cost of enzymes to improve the economics of the process. Process options using those enzymes will lead to the first large-scale, sugar-platform biorefineries.
- R&D advances have been identified to lower the cost of sugars for products including biofuels. As production costs for biofuels are reduced commensurately, larger fuel markets will become accessible. The technical challenge is to advance biomass processing to a level of maturity comparable to that of the existing petroleum industry.
- Biobased products will be key elements in the development of integrated processes for producing fuels, chemicals, and power.

Current Research, Development, and Demonstration

RD&D Goals

- By 2010, finalize a process flow diagram with material and energy balances for an integrated biorefinery with the potential for three bio-based chemicals or materials.
- By 2012, complete a system-level demonstration with corn kernels' fiber and recalcitrant starch aiming at 5% to 20% increase in ethanol yield from ethanol plants.
- By 2012, reduce the estimated cost for producing a mixed, dilute sugar stream suitable for fermentation to ethanol to \$0.10/lb, compared to the cost of \$0.15/lb in 2003. If successful, this cost goal would correspond to \$1.75 per gallon of ethanol, assuming a cost of \$45 per dry ton of corn stover.

RD&D Challenges

- Low-cost enzymatic hydrolysis process technologies need to be developed.
- Pretreatment cost, yield, and equipment reliability need to be improved.
- Process integration and optimization needs to be developed.
- Fermentation organisms need to be developed and improved.

RD&D Activities

- Evaluation of pretreatment options and advanced R&D to understand biomass feedstock mechanisms.
- Industrial partnerships for demonstrating biochemical conversion technology on corn stover.
- Joint DOE and USDA solicitations targeting key enabling technologies to meet the RD&D challenges.

Recent Progress

- Cargill-Dow, a corporate partner, has built a facility that can produce almost 300 million pounds of lactic acid annually from corn starch. The facility also converts lactic acid into PLA for the polymers markets.
- Genencor International has announced that it met the target of a 10X reduction in the cellulase portion of the production cost of ethanol from biomass. Novozyme Biotech has announced that it expects to achieve the same goal by the end of its subcontract in 2004 (goal achieved).
- Breakthroughs in genetically engineered microorganisms capable of fermenting the broad range of sugars found in biomass. These advances have led to an R&D 100 award and a number of patents.
- A conceptual design and cost estimate of a cellulosic ethanol facility has been completed and updated by DOE and engineering and construction firms. The report outlines the process necessary to meet cost targets.

Commercialization and Deployment Activities

- Conversion of cellulosic biomass to sugars and products from those sugars is not yet commercial. The U.S. capacity to produce ethanol from corn is 3 billion gallons annually. Ethanol is used as a fuel extender and, increasingly, as an oxygenating additive for reformulated gasoline wherever MTBE is phased down.
- Starch crops play a transitional role, but large-scale displacement of petroleum will rely on cellulose.
- About 15-21 million gallons of biodiesel is produced annually in the United States.
- Biobased products can replace 1:1 their chemically derived counterpart if the cost is competitive. This

approach is of interest to the existing biomass-processing community; their infrastructure is already in place.

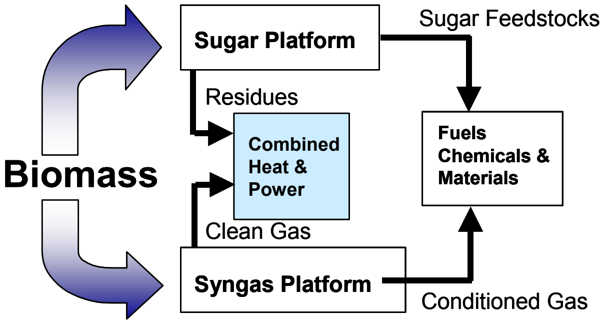
- Oil-based products or fuels have essentially a 1:1 displacement of petroleum-based products or fuels; this is attractive in efforts to reduce dependence on imported oil.
- Biobased products can bring new properties and functions to materials and chemical intermediates. This characteristic can enable biorefinery operations and the development of small businesses. Here, the market is not fully defined, capital risk is high, and time to commercialize may be long. Investments by the Federal government can lower some of these barriers.

Market Context

- For ethanol:
  1 Quad of biomass: 1% of projected petroleum imports for 2020
  5 Quads of biomass: 6% of projected petroleum imports for 2020
- For fuels and chemicals (depending on the mix of products):
  1 Quad of biomass: 0.5-1% of projected petroleum imports for 2020
  5 Quads of biomass: 5-10% of projected petroleum imports for 2020

2.3.6 THERMOCHEMICAL CONVERSION OF BIOMASS

Technology Description



Biomass resources are agricultural crops and residues, wood residues, grasses, and trees. Biomass absorbs CO_2 as it grows, offsetting the CO_2 emissions from harvesting and processing, and can be a substitute for fossil resources in production of power, fuels, and chemicals. Biomass feedstocks currently supply about 3 quadrillion Btus (Quads) to the nation's energy supply based primarily on wood resources. The potential exists for increasing total biomass contribution to 10 Quads nationwide, which would create positive impacts on farming and forest products industries. Cost, sustainable supply availability, biomass variability, and delivery systems are key challenges for biomass utilization. Use of biomass resources as an alternative to fossil resources reduces most emissions, including emissions of greenhouse gases (GHGs). Through use of materials that would normally be waste, biomass systems bring about a net sink for GHG emissions, because methane emissions that would result from landfilling are avoided.

Thermal conversion of biomass is a manufacturing platform comprised of many technology routes and involves use of heat to break down biomass feed into an oil-rich vapor in pyrolysis and/or synthesis gas in gasification, which is used for generation of heat, power, liquid fuels, and chemicals. Technologies in this platform can provide the basis for a biorefinery, or be combined with other platform technologies. One advantage of thermal conversion processes is that they can convert nearly all biomass feedstocks into synthesis gas, including some feedstock components that are difficult to process by chemical or biological means.

The biorefinery is analogous to an oil refinery. Multiple feedstocks are thermally converted to a slate of products via multiple technology routes. Fuel production provides a large-volume product to achieve economies of scale, while lower volume biobased coproducts and power can improve the economic competitiveness of biomass as a sustainable source of energy. Integrated biorefinery systems are being evaluated for their feasibility in producing fuels and products for potentially large commercial markets. A major challenge is to develop the ability to convert the fractionated biomass components into value-added products as efficiently as the current petrochemical business of today.

Biomass combustion is a thermal process that converts biomass entirely to carbon dioxide and water vapor; and, thus, precludes conversion to intermediate fuels or chemicals. The existing biomass power industry primarily uses combustion to produce steam for heat and electricity generation. Co-combustion of biomass with coal, or "cofiring" has received recent interest as a way to reduce fossil carbon emissions from coal power plants. There are few significant technical barriers to increase use of these technologies.

System Concepts and Representative Technologies

Thermal conversion technology is important and has several key roles in an emerging bioeconomy:

- Most current biomass conversion is for heat and power generation and is based on direct combustion in small, biomass-only plants with relatively low electric efficiency of about 20%. Technology exists so that total system efficiencies can approach 90% if combined heat and power systems are applied. Most biomass direct combustion generation facilities use the basic Rankine steam cycle for electric power generation, which is made up of a steam boiler, an electric turbine, a condenser, and a pump. Evolution of combined cycles that integrate the use of gas and steam turbines can increase generation efficiency by up to two times. Cofiring of biomass with coal also can increase overall biomass-to-electricity conversion efficiency.
- A source of syngas for catalytic production of fuels, chemicals, and hydrogen is important. Once a clean synthesis gas is obtained, it is possible to access and leverage mature process technologies developed in the petroleum and chemicals industry for the production of a wide range of liquid fuels and chemicals.
- A source of heat and power for biorefinery operation. Virtually all other conversion processes – whether physical or biological – produce residue that cannot be directly converted to the primary product(s). In order to mitigate waste streams and to maximize the efficiency of the biorefinery, these residues can and

should be used for heat and power production. In existing biorefineries, residues are combusted in a steam boiler. There is a technological opportunity however, to use a gasifier coupled to a gas turbine combined cycle that can double conversion efficiency to electricity, while still producing steam from the gas turbine waste heat. Use of a biomass gasifier in a gasifier combined-cycle system can leverage on public and private investments in development of advanced- and next-generation gas turbine systems (more than $1 billion).

- Thermal conversion is a way to derive additional value from process residues. Within a biorefinery, thermal conversion and gasification can push many residues "up the value chain" through production of hydrogen or other higher-value products via thermal conversion to syngas followed by separation or synthesis steps.
- Gasification converts biomass to a syngas that can be substituted for natural gas in combustion turbines, shifted into hydrogen for fuel cell or other applications, or used in existing commercial catalytic processes for production of liquid fuels and chemicals. Several technologies exist in various stages of development for production of a suitable syngas, including indirect gasification, steam reforming of biomass, and gasification with oxygen or enriched air.
- Pyrolysis of biomass produces an oil-rich vapor that can be condensed for direct use as a fuel or as a hydrogen carrier, or refined for producing a variety of higher-value chemical products.

Technology Status/Applications

- The existing biopower sector, nearly 1,000 plants, is mainly comprised of direct combustion plants, with an additional small amount of cofiring (approximately 400 MW_e). Plant size averages 20 MW_e, and the biomass-to-electricity conversion efficiency is about 20%. Grid-connected electrical capacity was 9,700 MW_e in 2001; more than 75% of this power is generated in the forest products industry's combined heat and power applications for process heat. Combined utility and industrial generation in 2001 was more than 60 billion kilowatt-hours (about 75% of nonhydro renewable generation). Recent studies estimate that on a life-cycle basis, existing biopower plants represent a net carbon sink of 4 MMTC/yr. Biopower electricity prices generally range from 8¢–12¢/kWh.
- U.S. investment in equipment is $300-$500 M/year. At least six major engineering procurement and construction companies and several multinational boiler manufacturers are active.
- Biomass cofiring with coal ($50–$250/kW of biomass capacity) is the most near-term option for large-scale use of biomass for power-only electricity generation. Cofiring also reduces sulfur dioxide and nitrogen oxide emissions. In addition, when cofiring crop and forest product residues, GHG emissions are reduced by a greater percentage (e.g. 23% GHG emissions reduction with 15% cofiring).
- Small biopower and biodiesel systems have been used for many years in the developing world for electricity generation. OE is developing systems for village power applications for distributed generation that are more efficient, reliable, and clean for the developed world. These systems range in size from 3 kW to 5 MW, with field verification completed by the end of 2003.

Current Research, Development, and Demonstration

RD&D Goals

- Goals are being developed.

RD&D Challenges

- Feed Preparation/Gasification – Improved feed processing for operational reliability need to be developed.
- Gas Cleanup – Improved methods of removing contaminants from syngas and modifying gas composition are needed.
- Synthesis gas utilization – The feasibility and optimization of syngas use in fuels, chemicals, and heat/power applications needs to be demonstrated on both a laboratory and industrial pilot scale.
- System Integration – Careful integration of the entire conversion system to maximize efficiency and reduce costs is needed.
- Development of enabling technologies is needed so that industry can reduce their risk of development and reduce development-cycle time.

- Verification and quantification of environmental and other benefits of themochemically derived fuels and chemicals is needed.

RD&D Activities

- Core research in feed preparation and handling, gasification, gas cleanup and conditioning, syngas utilization, and sensors and controls.
- Solicitation(s) for industry and university core research in targeted areas addressing specific barriers, e.g., high-pressure feeder development, novel gasification concepts, gas cleanup, hydrogen production, and sensors and controls.
- Solicitation(s) for precommercial validation of integrated processes for distributed fuels, chemicals, and hydrogen; and for integrated biorefinery applications.
- Joint DOE and USDA solicitations targeted to key enabling technologies can have an impact on meeting RD&D challenges.
- USDA has extensive research in crop production and is beginning to fund community-based, small-system demonstrations in collaboration with DOE.

Recent Progress

- R&D 100 award for the Burlington, Vermont, gasifier (Future Energy Resources Corporation, Battelle, and DOE Labs).
- Successfully demonstrated NO_x reductions from cofiring in excess of cofired percentage.
- Completed life-cycle assessments verifying and quantifying environmental benefits of biopower systems.
- Successful energy crop (switchgrass and willow) harvesting and cofiring in Iowa, Louisiana, and New York.
- Public release of modeling software (BIOCOST) that allows evaluation of energy crop production cost scenarios.
- Annual switchgrass yields of more than 10 t/acre obtained from best test plots in three southern states.
- Successful collaboration between private industry, DOE, and the USDA-Forest Service to demonstrate the small-scale modular production of heat and power in community settings (schools, small businesses).
- Demonstration at commercial prototype scales the use of biomass-derived resins from bark for engineered wood products.

2.3.7 BIOMASS RESIDUES

Technology Description

Biomass residues are the organic byproducts of green plants used for food, fiber, and forest production and processing. Major sources of residues include grain crops such as corn, wheat, and rice; animal waste; forest harvest; fuel-reduction treatments, and processing. These residues can be used as an alternative fuel source and for other purposes. This profile addresses the issues of harvesting, storing, and transporting biomass residues.

System Concepts

- The sustainable use of biomass residues for energy requires understanding when and where residues can be removed from agricultural and forest soils without reducing long-term productivity.
- Under certain circumstances, residues may have greater economic and ecological value when left on the land to restore nutrients, reduce erosion, and stabilize soil structure than if harvested for fuel. Biomass residue energy production may be most effective in locations where crop yields and soil organic levels are high, and erosion is not a major concern.

Representative Technologies

- Agricultural residues (corn stover, straws from wheat, rice, and other grain crops).
- Wood residues resulting from lumber, furniture, and fiber production.
- Forest residues (tops and limbs from harvest for wood products, material from fuel reduction treatments).
- Black liquors from pulp production.
- Animal wastes from confined production of chickens, pigs, and cows.
- Clean wood from urban yard trimmings and construction/demolition.

Technology Status/Applications

- Sustainable and recoverable amounts of corn stover, wheat straw, rice straw, and cotton stalks are estimated at about 150 MdT/year (less than 50% of the amount actually produced). Some corn stover is being removed presently for production of chemicals and animal bedding. Straws are being used in Europe as a bioenergy resource.
- More than 2.1 quadrillion Btu of primary biomass energy is consumed by industry, and it generates 56 million MWh of electricity plus heat. Nearly two-thirds of this electricity is derived from wood and wood wastes (including spent pulping liquors, wood residues, byproducts from mill processing, and forest residues). About one-third of the electricity and heat is derived from municipal solid waste and landfill gas.
- Some technologies are available to combust or gasify animal wastes. The most widely known option is to capture methane gas, a byproduct of anaerobic digestion.

Current Research, Development, and Demonstration

RD&D Goals

- By 2006, establish measurable cost reductions in corn-stover supply systems with modifications of current technology.
- By 2007, develop whole-crop harvest systems for supplying biorefineries of multiple products.
- By 2010, develop enhancements to the whole-crop harvest systems that include fractionation for maximum economic return, including returns to soil for maximum productivity and conservation practices.
- By 2015, develop an integrated system for pretreatment of residues near harvest locations and a means of collecting and transporting partially treated substrates to a central processing operation.
- By 2020, develop fully integrated crop and residue harvesting, storage, and transportation systems for food, feed, energy, and industrial applications.

RD&D Challenges

- Develop environmental data to make decisions on residue removal from agricultural and forest lands.
- Assemble better information on the characteristics of residue feedstock to assist in cost-effective harvest/handling and storage systems, and to assist potential users in optimizing their systems to handle residue feedstock.
- Develop cost-effective drying, densification, and transportation techniques to create more "standard" feedstock from residues.

- Develop efficient and environmentally sound infrastructure for residue supply systems (collection, handling, storage, transport).
- Gain public acceptance for the removal of agricultural and forest residues where shown to be sustainable.
- Develop methods for estimating residue availability based on published or easily accessible information sources.
- Develop effective and publicly acceptable ways of using animal wastes.

RD&D Activities

- Reduce feedstock costs and enhance feedstock quality through improving and adapting the existing collection, densification, storage, transportation, and information technologies (precision agriculture and forestry) to bioenergy supply systems.
- Enhance the sustainability of feedstock supply enterprises (production and handling) by developing and servicing robust machines for multiple applications and extended use.
- Research the engineering properties of novel aqueous and nonaqueous multiphase bioenergy feedstocks.

Recent Progress

- Critical operations contributing to the cost of residue harvest have been identified. It is now clear that a reduction in the number of operations is the key to reduction in feedstock costs.
- Farm-equipment manufacturers in the United States are becoming increasingly aware of opportunities in biomass harvesting and handling systems. Large and small companies are building alliances with research institutions to develop equipment for handling large quantities of biomass.
- Green power producers are making greater use of landfill gas as a resource for electricity production.

Commercialization and Deployment Activities

- Use of biomass residues for bioenergy and bioproducts is already commercial where those materials are captured internally by an industry or where disposal fees are high enough to encourage delivery of these materials to an energy end user for little to no cost.

2.3.8 ENERGY CROPS

Technology Description

Energy crops are fast-growing, genetically improved trees and grasses grown under sustainable conditions for harvest at 1 to 10 years of age. End uses of energy crops include biomass power (combustion and gasification), biofuels (ethanol), and new bioproducts such as plastics and many types of chemicals.

System Concepts

- Biomass feedstock supply systems are widely available throughout the United States but locally optimized for climate and soil conditions and end-use requirements.
- Quantities must be sufficient to support large-scale processing facilities.
- In the future, some crops will likely be genetically tailored in a way that facilitates separations and conversion processes for selected end uses.

Representative Technologies

- Short rotation woody crops – selected tree varieties grown as single-stem trees under sustainable conditions for year-round harvest within 4-10 years with replanting assumed.
- Woody coppice crops – selected tree varieties grown as multistemmed “bushes” under sustainable conditions for year-round harvest.
- Perennial grass crops – selected high-yield varieties of grasses grown under agronomic conditions for fall and winter harvest with stand regrowth assumed for up to 10 years, involving some modification to standard forage harvest systems.
- Genetic improvement, pest and disease management, sustainability optimization, and harvest equipment development R&D ongoing for all of the above.

Technology Status/Applications

- Short-rotation woody crops are produced commercially in the Pacific Northwest and North Central regions of the United States and many parts of the world (Brazil, Australia, Spain, etc.) for combined fiber and energy use.
- Woody coppice crops are produced commercially in Northern Europe and are being adapted to and tested at an operational scale in New York.
- Perennial grass crops have high yield potential and have been demonstrated in south, southeastern, mid-west, and north-central parts of the United States. Technology is being tested as a biomass feedstock supply system for biomass power in Iowa.

Current Research, Development, and Demonstration

RD&D Goals

- By 2006, develop feedstock crops with experimentally demonstrated yield potential of 6-8 dry ton/acre/year and accompanying cost-effective, energy-efficient, environmentally sound harvest methods.
- By 2010, identify genes that control growth and characteristics important to conversion processes in few model energy crops – and achieve low-cost, “no-touch” harvest/processing/transport of biomass to process facility.
- By 2020, advance the concept of energy crops contributing strongly to meet biomass power and biofuels production goals – and increase yield of useful biomass per acre by a factor of 2 or more compared with yields in 2000.

RD&D Challenges

- Transfer genomics information gained from arabidopsis, rice, and corn to acceleration of domestication of poplars and switchgrass.
- Develop gene maps and increased functional genomics understanding for model crops.
- Develop an efficient infrastructure for energy crop supply and utilization systems.
- Scale up seed to large-scale commercial deployment.
- Demonstrate that energy crop production is sustainable and environmentally beneficial.
- Gain acceptance by the public for the use of genetic engineering of energy crops.
- Develop expertise on machinery and logistics aspects of agricultural and forest engineering.

RD&D Activities

- Crop yield improvement research on two model woody crops (poplars and willow) and one herbaceous species (switchgrass) is being conducted by researchers in academic and USDA research organizations in many locations throughout the country.
- Genetic maps have been developed for poplars and are in process for switchgrass; work has been initiated to identify genes important to accelerated domestication of poplars and switchgrass.
- Cost-supply relationships are being generated for energy crop supplies in different regions of the country.
- Environmental research to optimize energy crop sustainable production techniques is being conducted in a few locations.
- Research on control of diseases and pests through genetics and/or cultural management.

Recent Progress

- Yields of up to 10 dry tons/acre/year have been observed in small experimental plantings of poplars, willows, and switchgrass in selected locations with genetically superior material.
- Yields of 5-7 dry tons/acre/year have been measured in small pilot-scale regional field trials of energy crops in some locations.
- Two major industrial enzyme companies are developing a new generation of cellulase enzymes to support an enzyme sugar platform.
- Farmers are engaged in energy crop R&D in several regions of the country through federally supported demonstrations.
- An economic model for energy crop production costs has been released for public use.
- Joint USDA/DOE analysis on the economic impacts of bioenergy crop production on U.S. agriculture has shown the potential for net farm income to increase from $2.8 billion to $6 billion depending on production scenarios and feedstock prices.
- A nutrient cycling spreadsheet model applicable to forestry and short rotation woody crop applications has recently been completed and made available to industry and the public on the Web.

Commercialization and Deployment Activities

- Between 1983 and 1998, 70,000 acres of poplars were established commercially in the Pacific Northwest with significant utilization of new hybrid materials generated by the DOE-funded research programs. Opportunistic market conditions, together with short-rotation crop technology readiness and technology transfer activities, were all critical to the commercialization success in the Pacific Northwest.
- Other types of short-rotation crops – including eucalyptus, sweetgum, sycamore, and willow, and established in other parts of the country – contribute to an approximate total level of commercialization of short-rotation woody crops of about 120,000 acres. Willow contributes a partial wood supply to a cofiring biomass power demonstration project. Switchgrass is already a crop planted on many Conservation Reserve Program acres, and it is the feedstock supply for two biomass power cofiring demonstrations.

2.3.9 PHOTOCONVERSION

Technology Description

Photoconversion technology encompasses sunlight-driven quantum-conversion processes (other than solid-state photovoltaics) that lead to the direct and potentially highly efficient production of electrical power or fuels, materials, and chemicals from simple renewable substrates such as water, carbon dioxide (CO_2) and 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 bio-inspired.

A photoconversion process to produce hydrogen from metabolically engineered algae.

System Concepts

- Photoconversion processes use solar photons directly to drive biological, chemical, or electrochemical reactions to generate electricity, fuels, materials, or chemicals.
- System components include biological organisms or enzymes, semiconductor structures (photoelectrochemical cells, colloids, nanocrystals, certain plastics or polymers, quantum dots or nanoparticles, 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 produce electrical power, hydrogen, biodiesel, organic acids, methane, methanol, and plastics. These technologies also can remove CO_2 from the atmosphere through photoreduction of CO_2 to fuels, materials, and chemicals. Moreover, they can achieve atmospheric nitrogen fixation (independent of natural gas) and convert biomass to fuels, materials, or chemicals.
- Most of these technologies are at early stages of research, but some are at the development level, and some that produce high-value products are commercial.

Technology Status/Applications

- Power production: dye-sensitized, nanocrystalline, titanium dioxide semiconductor solar cells are 8%-11% efficient and are potentially very cheap. In contrast to solid-state PV solar cells, light is absorbed by dye molecules in contact with an electrolyte 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-by-8-foot panels using a system developed by Texas Instruments, and photochargeable batteries that include electrochemical storage have been demonstrated with 24-h power output. Hot-carrier photoconversion technology for increasing solar-conversion efficiencies (with theoretical efficiency limits of 65%-86%, depending on the solar photon concentration) is making progress. The term "hot carrier" refers to the utilization of highly energetic electrons (called hot electrons and created upon absorption of photons with energies larger than the semiconductor bandgap) for useful chemical production or electrical power, rather than converting the excess electron energy to heat by photon emission. In present photoconversion and photovoltaic devices, the hot electrons cool, and their excess energy is lost as heat in a picosecond (1E-12 sec) or less. Semiconductor nanostructures have been found to slow the cooling time of hot electrons by up to two orders of magnitude, thus enhancing the probability for hot electron conversion.

- 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 important advances have been made recently; 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 people involved in atmospheric control in small spaces (i.e., submarines and the space station) 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, as well as producing fertilizer from atmospheric nitrogen and renewable hydrogen, 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

- In the near-term, research will focus on applications related to electrical power and high-value fuels and chemicals, where commercial potential may be expected during the next 5 to 10 years. If successful, larger-scale applications of photoconversion technologies may follow in the period from 2010 to 2015, with materials and fuels production beginning in the period 2015 to 2020, and commodity chemicals production in the period from 2020 to 2030.

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 biomimetic components. Progress in 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

- A significant level of basic research activities in solar photoconversion is currently being performed by the DOE Office of Science; some exploratory R&D is being performed by DOE Office of Energy Efficiency and Renewable Energy/Office of Solar Technologies.
- Some basic research support by the National Science Foundation and the U.S. Department of Agriculture is complementary.

Recent Progress

- Prototype dye-sensitized nanocrystalline semiconductor solar cells have been demonstrated as power sources in small niche markets. Commercial interest is very high because they also can be configured to produce hydrogen.
- Scientific breakthroughs during the past seven years have been made in microbial and enzymatic R&D; natural photosynthesis; semiconductors, nanostructures, quantum dots, and superlattices; CO_2 catalysis; and energy and electron transfer in artificial donor/acceptor molecules.

Commercialization and Deployment Activities

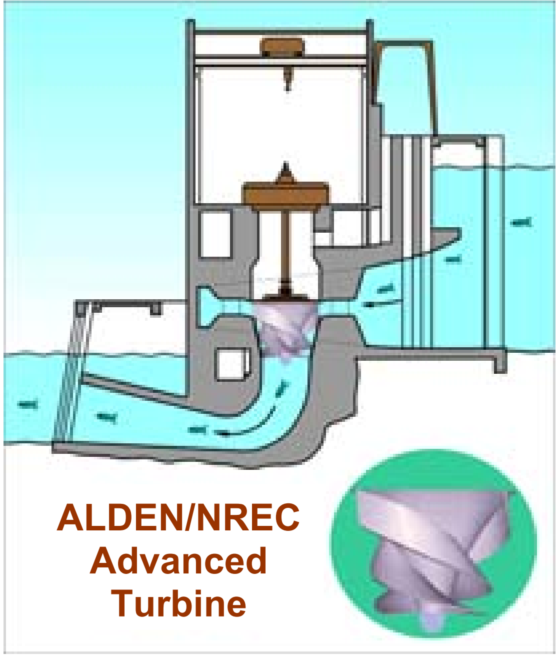
- Astaxanthin, a pigment synthesized from petroleum, is used as a coloring agent in the poultry and salmon industries. Algal production of the pigment just started in Hawaii and is replacing the fossil version for health and environmental reasons. Large-scale algal ponds are producing high-value chemicals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

Market Context

- Besides the applications discussed above, many spin-off technologies are possible. These include optoelectronics, biosensors, biocomputers, bioelectronics, and nanoscale devices.

2.3.10 ADVANCED HYDROPOWER

Technology Description



Hydroelectric power generates no greenhouse gas. To the extent that existing hydropower can be maintained or expanded through advances in technology, it can continue to be an important part of a greenhouse gas emissions-free energy portfolio. Advanced hydropower is technology that produces hydroelectricity both efficiently and with improved environmental performance. Traditional hydropower may have environmental effects, such as fish mortality and changes to downstream water quality and quantity. The goal of advanced hydropower is to maximize the use of water for generation while improving environmental performance.

System Concepts

- Conventional hydropower projects use either impulse or reaction turbines to convert kinetic energy in flowing or falling water into turbine torque and power. Source water may be from free-flowing rivers, streams, or canals, or water released from upstream storage reservoirs.
- New environmental and biological criteria for turbine design and operation are being developed to help sustain hydropower's role as a clean, renewable energy source – and to enable upgrades of existing facilities and retrofits at existing dams.

Representative Technologies

- New turbine designs that improve survivability of fish that pass through the power plant.
- Autoventing turbines to increase dissolved oxygen in discharges downstream of dams.
- 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.
- New assessment methods to balance instream-flow needs of fish with water for energy production and to optimize operation of reservoir systems.
- Advanced instrumentation and control systems that modify turbine operation to maximize environmental benefits and energy production.

Technology Status/Applications

- Hydropower provides about 78,000 MW of the nation's electrical-generating capability. This is about 80 percent of the electricity generated from renewable energy sources.
- Existing hydropower generation faces a combination of real and perceived environmental effects, 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
- DOE's Advanced Hydropower Turbine System (AHTS) program will be completing public-private partnerships with industry to demonstrate the feasibility of new turbine designs (e.g., aerating turbines at the Osage Dam, and a Minimum Gap Runner turbine at the Wanapum Dam).

Current Research, Development, and Demonstration

RD&D Goals

- By 2006, the completion of testing of hydroelectric turbine technology capable of reducing the rate of fish mortality to 2%, which would equal or better other methods of fish passage (e.g., spillways or fishways).
- Also in the near term, the goal is to complete the development of the Advanced Hydro Turbine Technology in support of maintaining hydroelectric generation capacity due for relicensing between 2010 and 2020.

RD&D Challenges

- Biological design criteria for new technology are limited by poor understanding of how fish respond to turbulent flows and other physical stresses inside turbines and downstream of dams.
- To affect public perception, field-testing will be needed to provide the evidence that fish survival through turbines is equal to or greater than survival in other passage routes around dams. Regulatory trends are shifting power plant operation from peaking to baseload, effectively reducing the energy value of hydroelectricity and reducing plant capacity factors; higher instream-flow requirements are reducing total energy production to protect downstream ecosystems, but scientific justification is weak.

RD&D Activities

- DOE’s AHTS program constructed a test facility for pilot-scale testing of a new turbine design to evaluate hydraulic and biological performance; testing at this facility was completed in FY 2003.
- New biological design criteria to protect fish from shear and pressure have been developed in controlled laboratory experiments; computational fluid dynamics modeling and new sensor systems are producing new understanding of turbulence in turbines and draft tubes.
- Regional efforts by the Army Corps of Engineers and Bonneville Power Administration are producing solutions to some site-specific problems, especially in the Columbia River basin; but they are not addressing the national situation that is driven by market pressures and environmental regulation.
- Resource assessments of low-head and low-power resources were completed and analyzed.

Recent Progress

- TVA has demonstrated that improved turbine designs, equipment upgrades, and systems optimization can lead to significant economic and environmental benefits – energy production was increased approximately 12% while downstream fish resources were significantly improved.
- Field-testing of the Kaplan turbine Minimum Gap Runner design indicates that fish survival can be significantly increased, if conventional turbines are modified. The full complement of Minimum Gap Runner design features will be tested at the Wanapum Dam in FY 2005.

Commercialization and Deployment Activities

- Voith Siemens Hydro Power and the TVA have established a 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.
- In a competitive solicitation, DOE accepted proposals for advanced turbine designs from Voith Siemens, Alstom, American Hydro, and General Electric Co., field verification and testing is underway with some of these designs to demonstrate improved environmental performance.
- Flash Technology is developing strobe lighting systems to force fish away from hydropower intakes and to avoid entrainment mortality in turbines. Implementation at more sites may allow improved environmental performance with reduced spillage.

Market Context

- 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 (i.e., no new dams required for development) and more than 30 GW of undeveloped hydropower.
- Retrofitting advanced technology and optimizing system operations at existing facilities would lead to at least a 6% increase in energy output – if fully implemented, this would equate to 5 GW and 18,600 GWh of new, clean energy production.

2.3.11 GEOTHERMAL ENERGY

Technology Description

Geothermal energy is heat from within the Earth. Hot water or steam are used to produce electricity or applied directly for space heating and industrial processes. This energy can offset the emission of carbon dioxide from conventional fossil-powered electricity generation, industrial processes, building thermal systems, and other applications.

System Concepts

- Geophysical, geochemical, and geological exploration locates resources to drill, including highly permeable hot reservoirs, shallow warm groundwater, hot impermeable rock masses, and highly pressured hot fluids.
- Well fields and distribution systems allow the hot fluids to move to the point of use, and afterward, back to the earth.
- Utilization systems may apply the heat directly or convert it to another form of energy such as electricity.

Representative Technologies

- Exploration technologies identify geothermal reservoirs and their fracture systems; drilling, reservoir testing, modeling optimize production, and predict useful lifetime; steam turbines use natural steam or hot water flashed to steam to produce electricity; binary conversion systems produce electricity from water not hot enough to flash.
- Direct applications use the heat from geothermal fluids without conversion to electricity.
- Geothermal heat pumps use the shallow earth as a heat source and heat sink for heating and cooling applications.
- Coproduction, the recovery of minerals and metals from geothermal brine, is being pursued. Zinc is recovered at the Salton Sea geothermal field in California.

Technology Status/Applications

- With improved technology, the United States has a resource base capable of producing up to 100 GW of electricity at less than 5¢/kWh.
- Hydrothermal reservoirs are being used to produce electricity with an online availability of up to 97%; advanced energy-conversion technologies are being implemented to improve plant thermal efficiency.
- Direct-use applications are successful throughout the western United States and provide heat for space heating, aquaculture, greenhouses, spas, and other applications.
- Geothermal heat pumps continue to penetrate markets for heating/cooling (HVAC) services.

Current Research, Development, and Demonstration

RD&D Goals

- By 2010, for “flash” power systems, reduce the levelized cost of power generated by conventional (hydrothermal) geothermal resources from 6.1 cents per kWh in 2000 to 4.3 cents per kWh.
- By 2010, for “binary” power systems, reduce the cost from 8.7 cents per kWh in 2000, to 6.1 cents per kWh.

RD&D Challenges

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

RD&D Activities

- DOE Office of Energy Efficiency and Renewable Energy promotes collaborations among laboratories, universities, states, and industry. Industry provides access to operating fields and well data, equipment and geothermal materials, and matching funds. Related activities are supported by DOE Office of Fossil Energy and Office of Science.

Recent Progress

- The DOE Geothermal Program sponsored research that won two R&D 100 Awards in 2003: Acoustic Telemetry Technology, which provides a high speed data link between the surface and the drill bit; and Low Emission Atmospheric Monitoring Separator, which safely contains and cleans vented steam during drilling, well testing, and plant start-up.
- A second pipeline to carry replacement water has been completed through the joint efforts of industry and Federal, state, and local agencies. This will increase production and extend the lifetime of The Geysers Geothermal Field in California. The second pipeline adds 85 MW of capacity.

Commercialization and Deployment Activities

- Costs at the best sites are competitive at today’s energy prices – and investment is limited by uncertainty in prices; lack of new, confirmed resources; high front-end costs; and lag time between investment and return.
- Improvements in cost and accuracy of resource exploration and characterization can lower the electricity cost; demonstration of new resource concepts, such as enhanced geothermal systems, would allow a large expansion of the U.S. use of hydrothermal when economics become favorable.

Market Context

- Hydrothermal reservoirs have an installed capacity of about 2,400 MW electric in the United States and about 8,000 MW worldwide. Direct-use applications have an installed capacity of about 600 MW thermal in the United States. About 300 MW electric are being developed in California, Nevada, and Idaho.
- Geothermal will continue production at existing plants (2.2 GW) with future construction potential (100 GW by 2040). Direct heat will replace existing systems in markets in 19 western states.
- By 2015, geothermal should provide about 10 GW, enough heat and electricity for 7 million homes; by 2020, an installed electricity capacity of 20,000 MW from hydrothermal plants and 20,000 MW from enhanced geothermal systems.