SOLAR ENERGY

Solar energy represents a potentially limitless source of energy. Roughly 10,000 times as much solar energy falls on the surface of the Earth each year as is consumed in the form of fossil and nuclear fuel. The United States consumed approximately 88 EJ (8315×10^{15} Btu) of primary energy in 1993, about a quarter of the world total. Petroleum (qv) accounted for 40% of U.S. energy needs, coal (qv) and natural gas (see Gas, natural) 25% each, and nuclear (see Nuclear reactors) 8% in 1993. In its various forms, solar energy provided for approximately 4% of the annual energy requirements of the United States in the mid-1990s (1). The actual contribution of solar energy to U.S. and world energy needs over the coming decades is expected to be strongly influenced by the economic and societal attractiveness of the technologies developed to convert the solar resource to useful energy forms. The rate of commercialization of solar technologies is dependent on the adoption of attractive, albeit novel, technology systems.

Solar energy is most certainly expected to make increasing contributions to the world energy supply in the twenty-first century. However, progress in research and development is needed to assure that solar technology achieves its potential. Greater reliance on solar energy provides secure indigenous supplies of energy that can be utilized with minimal environmental impact. Solar energy production usually involves the creation of local jobs, and most of the technologies can be implemented using relatively lower cost workers and materials.

Whereas much of the research and development effort has focused on techniques for generating electricity, solar energy is also capable of producing process or space heat, chemical energy, or even high value fuels and chemicals. In 1970 essentially all utilization of solar energy came from hydroelectric power, used to generate electricity, and wood (qv), used for cooking, space heating, industrial processes, and power generation (qv) at rather low thermodynamic efficiency. As of the mid-1990s, many of the advanced solar energy technologies such as wind power plants, solar thermal power plants, municipal waste energy plants, and alcohol transportation fuels are being added to the traditional forms (see Alcohol fuels; Fuels from biomass; Fuels from waste; Renewable energy resources).

Part of the desire to utilize solar energy results from the technologies being thought of as environmentally benign. These technologies use sunlight, rainwater, or wind as the energy resource and thus generally do not produce gaseous emissions or waste materials having adverse environmental impact (see Air pollution). Many of the most promising solar technologies, however, are still in the early stages of development. In order to reduce the environmental impact of growing world energy use, additional technological advances and cost reductions must be accomplished.

The intensity of incident sunlight is diffuse, having a peak power density of only 1 kW/m^2 at the Earth's surface at noon in the tropics. The efficiency of conversion of solar energy varies from a few percent for photosynthetic production of biomass to as much as 15–20% for production of electricity for some photovoltaic modules (see Photochemical technology; Photovoltaic cells). For this reason, progress in reduction of the intensity of energy demand is important and makes widespread use of solar energy more practical. The energy intensity of the U.S. economy declined by fully 30% between 1970 and 1990. During the same period the electricity sector share of the energy mix increased from 25 to 36%, and the U.S. Energy Information Administration projects a further increase to 36% by 2010. The trend toward electrification worldwide militates in favor of a shift to solar or renewable energy because many of the most promising solar conversion technologies naturally produce electricity.

Great progress in both cost and reliability of a number of emerging solar technologies was made during the 1980s and early 1990s. In addition, a much better understanding of the remaining technical hurdles to be surmounted in order to bring solar energy systems to market was provided. A number of innovative means of efficient conversion of resources into usable energy have been identified and are being explored. These include thin-film photovoltaics, high performance wind turbines, fast pyrolysis of biomass, anaerobic digestion of biomass, simultaneous saccharification and fermentation of cellulosic materials, and genetically engineered biomass production (see Chemurgy; Fuels from biomass; Genetic engineering; Thin films).

The technology and cost progress of the emerging solar technologies as of the mid-1990s is discussed herein. A significant level of private sector interest has led to advances in wind, solar thermal, and photovoltaic electricity systems, as well as various possibilities for advanced biomass utilization including gasification/electricity generation and the production of transportation fuels and chemicals from biomass feedstocks.

1. Wind Energy Technology

The use of wind as a renewable energy source involves the conversion of power contained in moving air masses to rotating shaft power. These air masses represent the complex circulation of winds near the surface of Earth caused by Earth's rotation and by convective heating from the sun. The actual conversion process utilizes basic aerodynamic forces, ie, lift or drag, to produce a net positive torque on a rotating shaft, resulting in the production of mechanical power, which can then be used directly or converted to electrical power.

The scope of the wind resource is widespread and less dependent upon latitude than other solar technologies. The accessible resource in the United States has been conservatively estimated to be capable of providing more than 10 times the electricity consumed therein. The intermittency of the wind resource, however, makes it impractical to base more than 10–20% of electricity generation on this resource until a suitable storage technology is developed. Wind is a very complex resource, existing in three dimensions, rather than the two associated with other solar resources. It is intermittent and strongly influenced by terrain effects. Moreover, there is a nonlinear (cubic) relationship between wind speed and power or energy available. This last factor is best illustrated by comparing good, excellent, and outstanding wind sites having average wind velocities of 5.5, 7.0, and 8.5 m/s, respectively. This 1.5-m/s difference results in the excellent site having 106% more available energy per unit than the good site for conversion to electricity; the outstanding site has 269% more available energy than the good site.

Wind machines can be classified as either horizontal-axis or vertical-axis designs and typically utilize either two or three airfoils, as shown in Figure 1. Vertical-axis wind machines include both the Darrieus and Savonius designs. The Darrieus machine requires an auxiliary starting mechanism in order to produce useful energy. Commercial interest has centered on horizontal-axis machines more recently, partly because of the need to elevate most of the structure of the vertical-axis machines for maximum effectiveness. During the 1970s, large government-supported demonstration projects in the United States focused on the design and testing of very large machines of capacity from 2–5 MW. More recent commercial designs are evolving toward machines having capacities between 200–500 kW each. These smaller machines are usually grouped into wind farms of total capacity of 20 MW or more. Wind turbines of much smaller (10 kW) capacity are finding increased application for rural electrification, particularly in developing countries.

Wind energy, which has proved to be the most cost-competitive and utilized solar technology for the bulk power market, is one of the fastest-growing electricity generating sources worldwide. In 1995 alone, wind generating capacity grew by 32% to a total of 4900 MW (2). Although the United States has led in installed wind capacity, having 1650 MW at the end of 1995, most recent growth, ca 1996, has come from projects in Europe and Asia. As a result of early operating experience in California, the industry has improved turbine

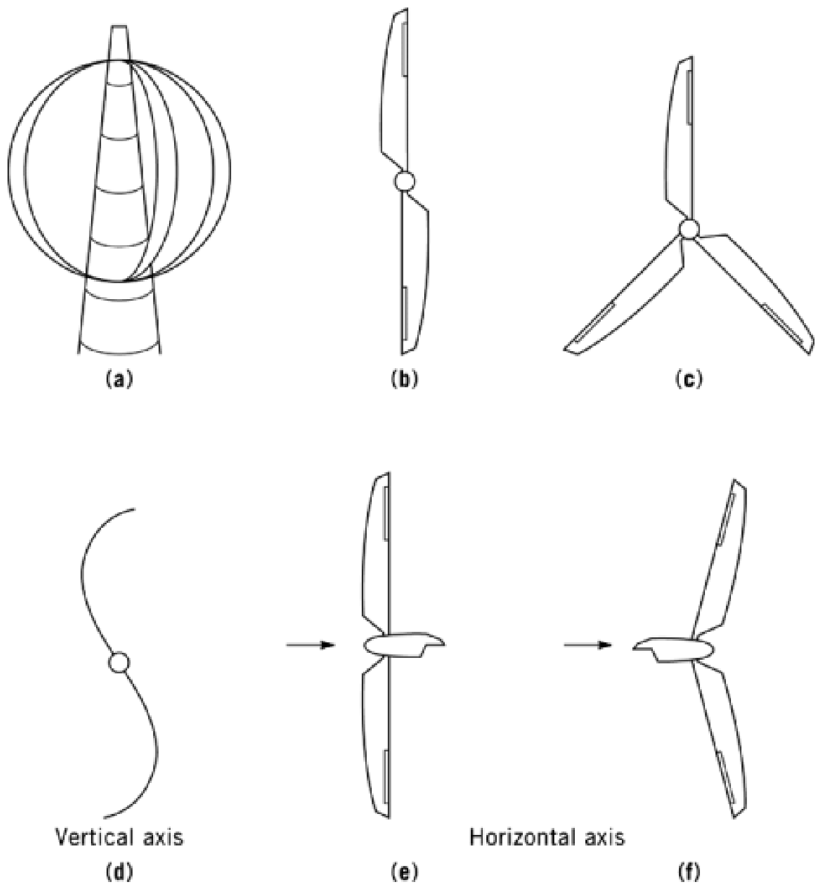

Fig. 1. Categories of wind machines: (**a**) Darrieus machine; (**b**) two-bladed machine; (**c**) three-bladed machine; and (**d**) Savonius machine. Parts (**e**) and (**f**) represent upwind and downwind placement, respectively.

technology and operating strategies such that installations reliably produce energy at costs that as of 1996 rivaled those of most conventional resources.

Wind technology provides economical energy to remote areas and for specialized applications. The modularity and wide size range of wind turbines available enable wind energy to serve many applications. Examples are small radio transmitters, offshore oil rigs, navigational aids, and remote communities. By combining the intermittent wind energy with backup power sources such as diesel generators or storage devices, most loads can be reliably and competitively served.

An issue for traditional electricity generation and distribution grids centers on how wind and other intermittent solar technologies should be considered relative to capacity credits. Historically, little if any capacity credit was given because wind cannot be considered dispatchable nor can the output be relied on to coincide with utility loads. Improved weather forecasting techniques as well as greater geographic dispersal of wind farms are expected to help mitigate this concern, but consistent methodologies are needed. In the longer term, the cost of generating wind energy could fall to the point where it is less expensive than the cost of the fuel for a fossil-fired power plant connected to the same utility grid. In that eventuality, wind energy would be used to extend fossil fuel reserves; conventional power plants would then be used to firm up the intermittent wind resource.

Wind energy has little or no impact on flora, fauna, climate, materials, or in terms of human health hazards. It does, however, have a potential negative impact on land use. On the negative side, three siting considerations require mention: the visual impact of large, rotating structures; the nearby acoustic disturbance associated primarily with the generation of aerodynamic forces on the rotating airfoils; and concerns about the possibility of bird kills from the rotating blades. In general, experience has shown the first two factors to be minimal, as long as the turbines are not located in proximity to populated areas. Considerable study has gone into the issue of bird kills (3). Mitigation of this factor may simply depend on a redesign of the wind turbine support tower so as to minimize available perches for avian raptors.

On the positive side, the three-dimensional nature of the resource provides it with a distinct advantage compared to other solar technologies. Specifically, because siting usually involves placing the individual turbines as high as possible, typically spacing turbines about 2 to 3 blade diameters apart crosswind and 10 diameters apart downwind, only a small fraction of a wind farm area is actually occupied. The rest of the land remains available for other applications, such as crop production or livestock grazing.

Performance of wind turbines, as well as other sources of energy, must be judged by the cost of energy (COE), ie, the levelized cost per kilowatt hour of electricity produced. For wind turbines, this cost can be determined from only a few parameters: the capital cost (in $\$/m^2$, including all balance of system costs), the annual energy capture (in kWh/m^2), and the operation and maintenance/replacement costs (annualized to $/kWh). Costs in California in 1995 were $0.07 to $0.10/kWh, derived from capital costs of about $\$450/m^2$, annual energy capture of 600–800 kWh/m^2, and operation and maintenance/replacement costs of $0.012 to $0.014/kWh. These cost and energy figures represent a significant improvement over the values for machines installed in the early 1980s, particularly with respect to capital costs. To tap a significant portion of the accessible resource mentioned, however, performance must be improved.

Potential incremental technological advancements that in aggregate would represent a dramatic improvement in turbine performance are shown in Figure 2. Whereas these improvement areas are broadly defined because of the uncertainty associated with long-term research, near-term improvement possibilities are fairly well defined. Initial improvements to existing designs are expected to occur through the use of advanced design tools, including turbulence codes, aerodynamic and structural codes, and fatigue life models (see Computer-aided design and manufacturing (CAD/CAM)). Also included is the use of advanced airfoils designed specifically for wind turbines to increase both energy output and rotor fatigue life. Site tailoring refers to the optimization of system designs for site-specific characteristics. Examples might include tall towers for locations having a strong vertical wind shear and control strategies optimized for different turbulence levels that would maximize power output while minimizing operation in damaging wind conditions. Operating strategies include the possible use of power electronics that allow the speed of the rotor to vary with wind speed while maintaining constant frequency power output thus allowing the turbine to operate at optimum efficiency over a wide range of wind speeds. Possible array spacing strategies are also being investigated to maximize energy capture over large arrays of wind turbines. The optimum spacing of turbines, both within and between rows, is dependent on the terrain as well as predominant atmospheric conditions. Other strategies include varying the heights of adjacent turbines to promote mixing in the boundary layer. This would reduce wake energy deficits and turbulence effects for downstream rows of turbines.

For the longer term, configurations and advanced designs that achieve dramatically improved reliability and manufacturability are sought. Rotors designed to withstand the fatigue loads that are only beginning to be understood would provide the reliability needed. Advanced designs might include new, highly flexible, lightweight rotors that are relatively insensitive to high wind turbulence levels. Greater strength or flexibility at reduced weights and costs are desired, as is optimum manufacturability of the advanced turbines. The goal of the improvements is to reduce the COE from wind energy. A reduction to 30–40% of 1995 levels should be possible.

Achievement of development goals is expected to lead to cost reductions such that cost-effective machines at a good site should produce electricity at ~$0.05/kWh.

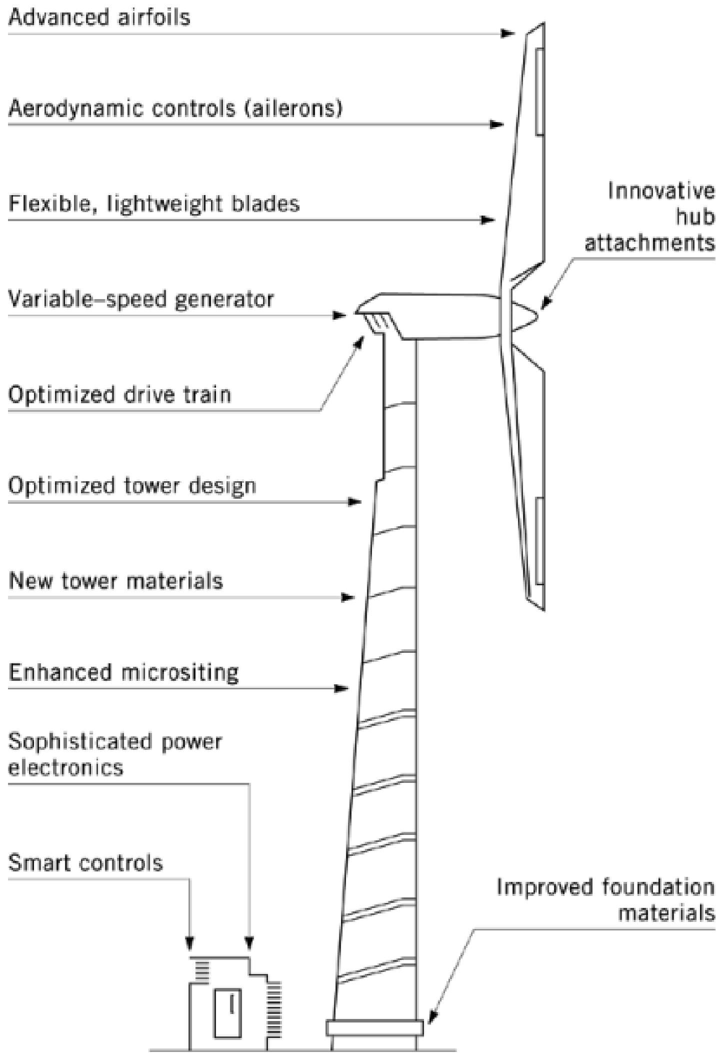

Fig. 2. Potential incremental improvements in wind turbine technology.

The issues of facilitating options such as energy storage and transmission may prove to be important to the success of wind energy technology. Cost-effective storage coupled to wind systems would yield capacity credit benefits. In addition, because sites are often isolated, the value of wind energy would benefit from transmission/distribution access.

2. Solar Thermal Electric Technology

Use of concentrated sunlight to generate electricity by thermodynamic processes is well documented (4). Reflective surfaces concentrate incident sunlight onto a receiver, where it is absorbed into a working fluid that powers a thermal conversion–generator device. Solar thermal systems, operating either with storage

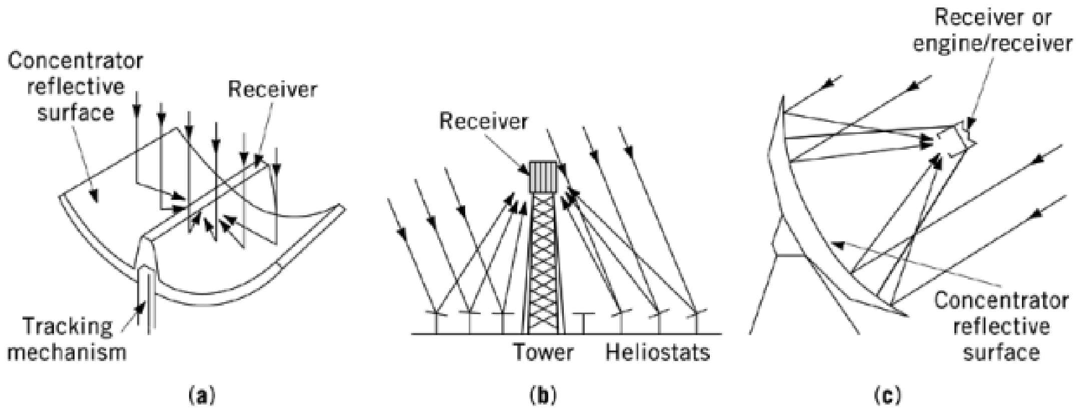

Fig. 3. Solar thermal designs: (**a**) parabolic trough; (**b**) central receiver; and (**c**) parabolic dish.

or in a hybrid mode with an auxiliary fuel, offer significant potential as capacity to meet utility peaking or intermediate electric power-generation needs.

Three main types of concentrating collectors have evolved for use in solar thermal systems: low concentration parabolic troughs, high concentration parabolic dishes, and central receivers (Fig. 3). Higher concentration produces higher temperatures in a working fluid and makes electrical generation more efficient.

Parabolic trough systems use surface reflectors to concentrate sunlight onto a fluid-filled receiver tube that is positioned along the line of focus. Concentration ratios of more than 100 times are typically used to generate temperatures of 400–500°C. Troughs are modular and many can be grouped together to produce large amounts of heated fluid. The fluid is then transported to a nearby facility to generate electricity.

The modular parabolic troughs and dishes are classified as distributed systems, whereas central receiver systems, in which heliostats are deployed in a central receiver configuration by placing large numbers of them around a tower-mounted receiver, are more centralized. All concentrating systems have their best annual output in regions where direct insolation is highest. Examples are the southwestern United States and other semiarid regions of the world. These systems also can be utilized, at slightly higher cost, in other geographical areas having somewhat lower levels of direct insolation.

All solar thermal electric system types have been demonstrated in industrial-like settings. A 10-MWe experimental central receiver power plant, Solar One, was deployed by a joint government–industry team and operated successfully by the Southern California Edison Utility on its grid for six years. Whereas system efficiency (7.4%) for this plant was somewhat below the initial predictions, extensive operational experience was gained and the plant delivered more than 37,000 MWh net energy to the grid, achieving 99% heliostat availability and 96% overall availability for the entire plant. The next generation plant, Solar Two, has been designed to incorporate modifications to the central receiver and heliostat design. The central receiver is to use molten salt as the working fluid and should mitigate most of the problems attributable to intermittency of sunlight encountered using Solar One. Annual system efficiencies of 14–15% and costs of $0.08–0.12/kWh have been projected for this plant.

Prototype parabolic dish electric systems totaling about 5 MWe have also been operated in utility settings in Georgia and in southern California. More recent development of a dish-mounted engine–generator has led to significant increases in system performance as compared to the earlier designs which collect the heat as thermal energy and transport it to a central location for electric generation. Indeed, a dish/Stirling engine–generator model has achieved a 29% overall system conversion of sunlight to electricity (5).

As of this writing (1996), 354 MWe of privately funded, parabolic-trough electric generating capacity was operating in California. These trough systems operate in a hybrid mode, using natural gas. Collectively they accounted for more than 90% of worldwide solar electric capacity. The cost of these systems fell steadily from \$0.24/kWh for the first 14-MW system to an estimated \$0.08/kWh for the 80-MW plant installed in 1989 (5).

Impressive technologies have reduced technical and financial risks in solar thermal electric technology. Although first-generation solar thermal systems have proved successful, the 1991 bankruptcy of the primary solar trough development company, Luz International, Ltd., offered insight into the challenges faced in the introduction of a new electricity generation technology. This bankruptcy was the result of a complex interplay between the unanticipated elimination of federal and state tax benefits and a sharp drop in the levelized cost of electricity beginning in the mid-1980s as advanced gas turbines using natural gas became available (6). Following this bankruptcy, solar thermal trough plants have been successfully operated at Kramer Junction, Daggett, and Harper Lake, California by separate operating companies.

International markets also provide an opportunity for solar thermal technology. Small systems, such as a prototype 7-kW parabolic dish/Stirling engine system under development by the Cummins Power Generation Company, have the potential to be competitive in either grid-connected or stand-alone applications in many third world countries. Science Applications International has developed a similar design using a 25-kW dish system which is to be tested as part of a government–industry joint venture in the United States.

The cost of energy from solar thermal electric systems, which was \$0.24/kWh in 1984, was reduced to \$0.08–0.12/kWh by the mid-1990s. Components that provide further improvement have been developed and are being evaluated. Dish electric systems utilizing a stretched-membrane dish integrated with a reflux receiver and a reliable Stirling engine, when developed and mass-produced, are projected to achieve \$1200/kWe. Cost estimates for energy from such a dish electric system are projected to reach \$0.05/kWh, low enough to be competitive with fossil fuel power generation.

3. Photovoltaics

Photovoltaic devices typically consist of a series of thin semiconductor layers that are designed to convert sunlight to direct-current electricity (see Semiconductors). As long as the device is exposed to sunlight, a photovoltaic (PV) cell produces an electric current proportional to the amount of light it receives. The photovoltaic effect, first observed in 1839, did not see commercial application until the 1950s when photovoltaic modules were used to power early space satellites. Many good descriptions of the photovoltaic phenomenon are available (7).

Photovoltaic devices produce electricity from incident direct or diffuse sunlight. Figure 4 shows a schematic of the operation of a photovoltaic device. These devices have no moving parts and thus are extremely reliable. Moreover, their operation does not release any effluent to the atmosphere. Costs, however, were relatively high compared to the operation of bulk electricity generation technologies as of the mid-1990s and the output of photovoltaics were intermittent because of variations in sunlight. Despite these limitations, the growth in demand for photovoltaic systems averaged about 30% per year throughout the 1980s and early 1990s.

The smallest unit of a PV system is called the PV cell. Cells are manufactured using crystalline and amorphous forms of silicon, copper indium diselenide [12018-95-0] (CIS), cadmium telluride [1306-25-8], and gallium arsenide [1303-00-0] as well as even more exotic materials. Photovoltaic systems generally consist of a flat layer of semiconductor material encapsuled by a glass or plastic cover, or of individual high efficiency PV cells incorporated in an optical arrangement to concentrate the sunlight. This latter arrangement often requires a solar tracking system, whereas the former, flat plate arrangement is normally installed at a fixed angle determined by the latitude of the site. Both types of PV devices are progressing about equally toward reduced cost.

Modules, the building blocks of large PV systems, are aggregates of PV cells large enough to provide convenient levels of electrical power. These modules can be 0.1 m^2 to more than 2 m^2 and can be expected to produce from 0.5 to 2 W/m^2 of power during a clear midday, depending on the conversion efficiency of the cell

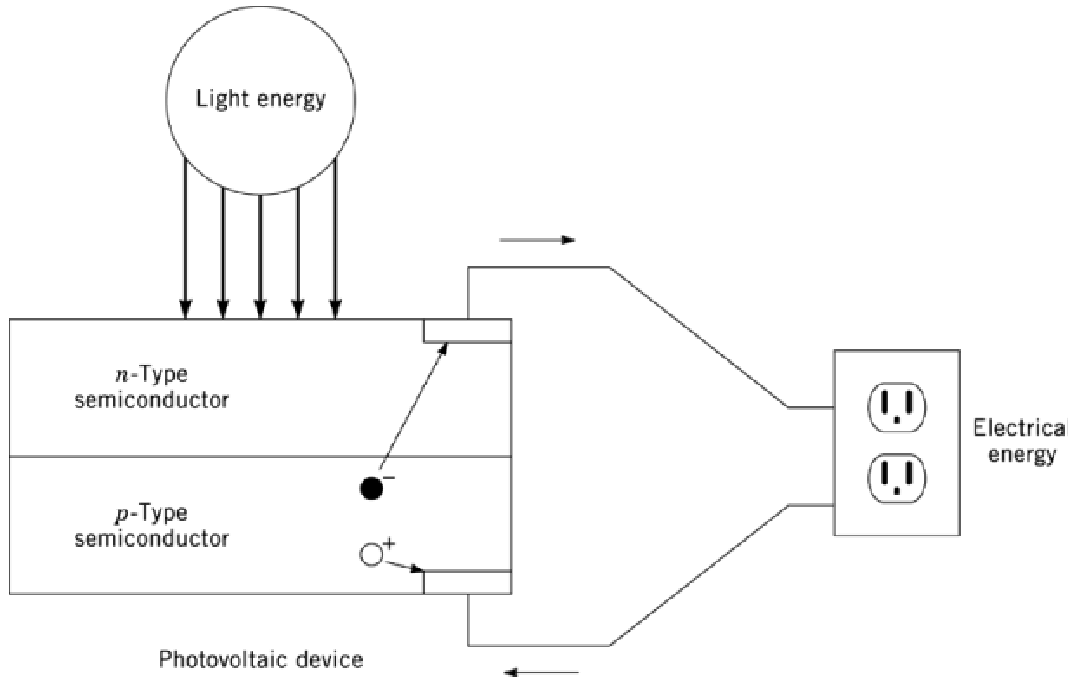

Fig. 4. Schematic illustrating operation of a photovoltaic cell.

material. The efficiency is defined as the ratio of electricity produced to the amount of sunlight incident on the PV device and is a critical figure-of-merit characterizing all PV cells, modules, and systems. The output power of a module at noon on a clear day is called its peak-watt power because it represents a maximum typical output. A module characterized as 100 Wp produces 100 W of power during a clear midday.

The efficiency of the flat-plate modules ranged from about 5% to almost 15% in 1995. Concentrator modules had correspondingly higher efficiencies and costs. The improvement in efficiency for a number of promising PV materials is shown in Figure 5. Two other important parameters are lifetime and module cost. Lifetimes range from a few years, for some of the newer technologies, to 20 years or more for crystalline silicon modules. Module costs were in the range of \$200–\$500/m^2 as of 1995 and showed a continual decline that was expected to be ongoing. Indeed, photovoltaic modules were increasingly being mass-produced and therefore likely to benefit from the economies of mass production. Figure 6 demonstrates the kind of manufacturing learning curve which would be expected for such a technology into the year 2000.

Unlike solar thermal systems or PV concentrator systems, the PV flat plate systems work well in cloudy locations because these latter convert diffuse as well as direct sunlight to electricity. On an annualized basis, the energy produced by a photovoltaic array varies by only about $\pm 25\%$ from an average value for the contiguous 48 states of the United States. As a result, it is practical to use photovoltaic systems in normally cloudy locations such as Seattle or northern Maine.

The terrestrial PV market has three principal segments: consumer products, remote power, and utility generation. The consumer product market was one of the first economic applications of the technology and is characterized by millions of small, milliwatt-sized cells powering calculators and watches. This market, which had been more than 5 MW/yr in the early to mid-1990s, is expanding to larger systems, eg, for battery charging and walkway lighting, reaching power levels near those used for the remote power application market (see Batteries).

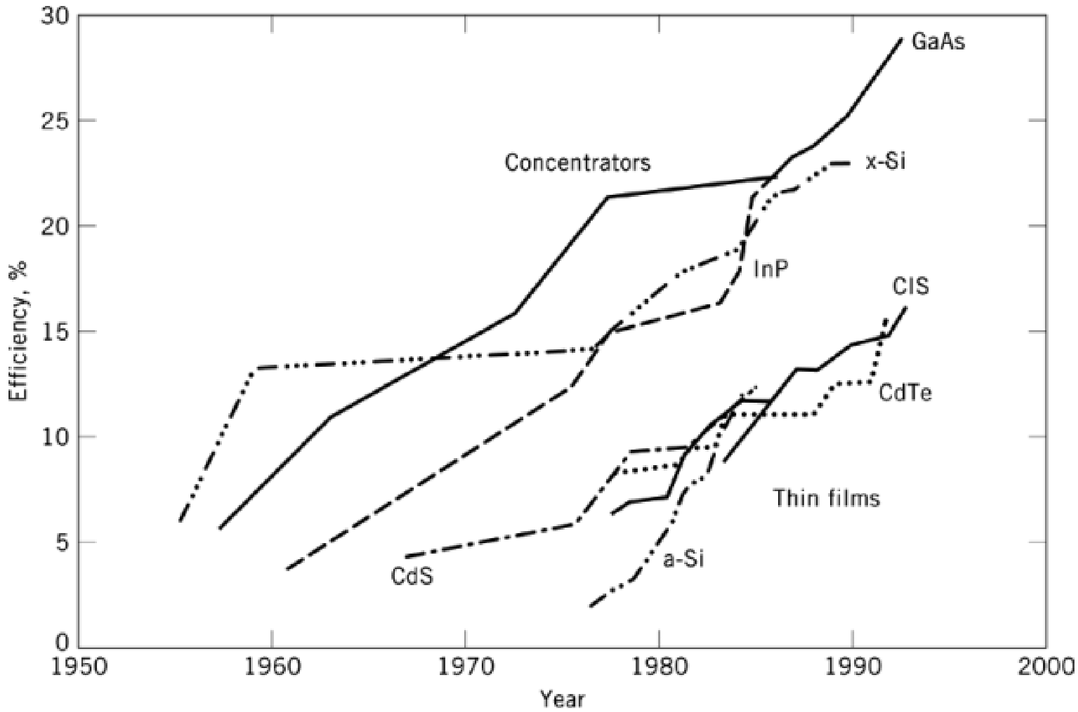

Fig. 5. Efficiency improvements in photovoltaic cells where (——) corresponds to GaAs; (– – –) InP; (–.–.) CdS; (....) CdTe; (..–..) amorphous silicon; and (–.....–) crystalline silicon. Courtesy of the National Renewable Energy Laboratory.

The largest use of PV is the remote power market. The self-contained and modular nature of PV systems has led to their adoption to meet power loads remote from the electric utility. These applications have come to be referred to as stand-alone because all of the energy needed by the load must come from on-site sources. Typical stand-alone uses are power for telecommunications, lighting, security systems, water supply, battery charging, cathodic protection, vaccine refrigeration, remote monitoring, rural housing, and small villages. The systems are economical because there is no reasonable alternative, such as for a microwave repeater on an inaccessible mountaintop, or because the alternative (often diesel generators) is too costly to install, operate, and refuel. The remote power market accounts for the vast majority of the sales by U.S. industry and is split about equally between international and domestic applications. The domestic customers are remote homeowners, companies purchasing for telecommunications, cathodic protection, and literally hundreds of other uses, as well as governmental agencies like the U.S. Coast Guard (navigation aids), the Department of Defense (battery chargers), and state highway departments (emergency call boxes). The international customers are governments or donor agencies involved in rural electrification and development. The mid-1990s rapid growth rate in PV sales was almost exclusively a result of the increase in sales for remote power. Photovoltaics have gained acceptance and recognition as a reliable and economical remote power source.

4. Biomass and Biofuels

Biomass is the term used to describe all plant-derived materials, whether wood (qv) or wood wastes, residue of wood-processing industries, food industry waste products, sewage or municipal solid waste (MSW), herbaceous

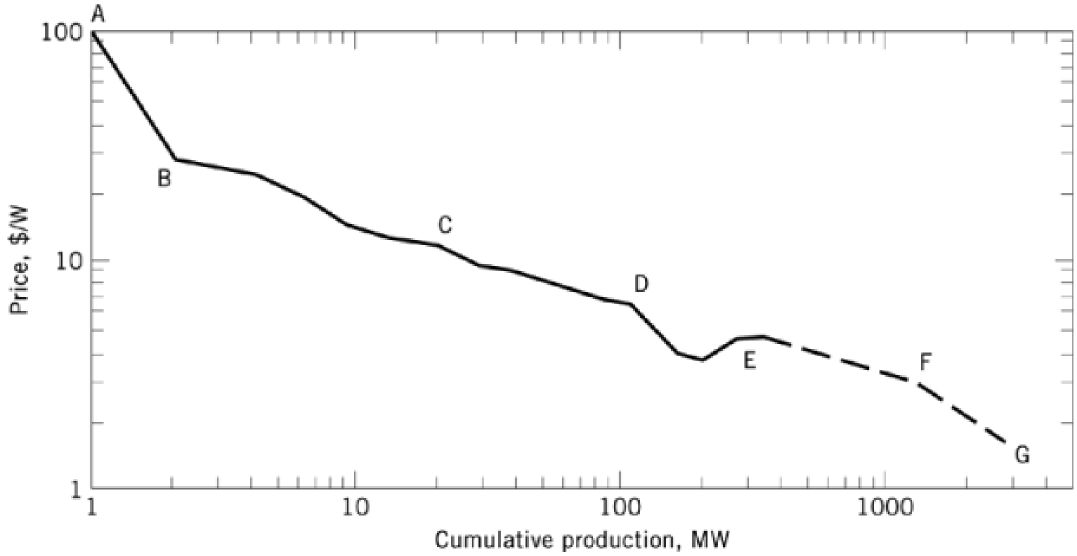

Fig. 6. Photovoltaic module experience where the dashed line corresponds to projected values. Point A represents the 1970 price of $100/W; B, the 1975 price of $30/W; C, the 1980 price of $12/W; D, the 1985 price of $6.75/W; E, the 1992 price of $5/W; F, the 1995 price at $3/W; and G, the year 2000, at <$2/W. Courtesy of the National Renewable Energy Laboratory.

or other biological materials cultivated as energy crops, or other biological materials. Biomass is both a principal and a prospective source of energy. Green plants use the sun's energy to convert CO_2 from the atmosphere to sugars during photosynthesis. Hence biomass is considered a form of solar or renewable energy. Unlike direct solar or wind, the solar energy in biomass is stored for later use. The conversion efficiency of photosynthesis is very low, however. The key feature of the biomass technology is the rapid ($\lesssim$20 yrs) recycling of the carbon fixed in the biological process. Unlike the burning of fossil fuels, Earth's reserves of which were ultimately derived from solar energy because these materials consist of degraded residues of plants and animals, combustion of biomass merely recycles the carbon fixed by photosynthesis in the growth phase and typically has no net impact on global carbon dioxide levels.

Biomass has been used as a source of energy throughout history, representing as of 1995 up to 35% of the primary energy used for cooking and heating in developing countries. The use of biomass or biofuels as a source of energy for space heating, process heat, electricity production, transportation fuels, or as an intermediate gaseous fuel is attractive not only for economic reasons wherever the fuel is readily available at low cost, but also for economic development and environmental reasons. The systems that convert biomass into usable energy can be modular and efficient on a relatively small scale. Both thermal supply and electric generation systems provide 24-h, base-load (dispatchable) output. Biomass is a renewable and indigenous resource that requires no foreign exchange. The agricultural and forestry industries that supply feedstocks also provide substantial economic development opportunities in rural areas. The pollutant emissions from combustion of biomass are usually lower than those from fossil fuels. Furthermore, commercial use of biomass may avoid or reduce problems of waste disposal in other industries, such as forestry and wood products, food processing (qv), and particularly MSW in urban centers. In addition, recycling (qv) of paper, glass, plastics, and metal products, at times performed in conjunction with municipal waste collection and combustion, can conserve energy resources required for the primary manufacture of these energy-intensive materials.

There are four principal ways in which biomass is used as a renewable energy resource. The first, and most common, is as a fuel used directly for space and process heat and for cooking. The second is as a fuel for

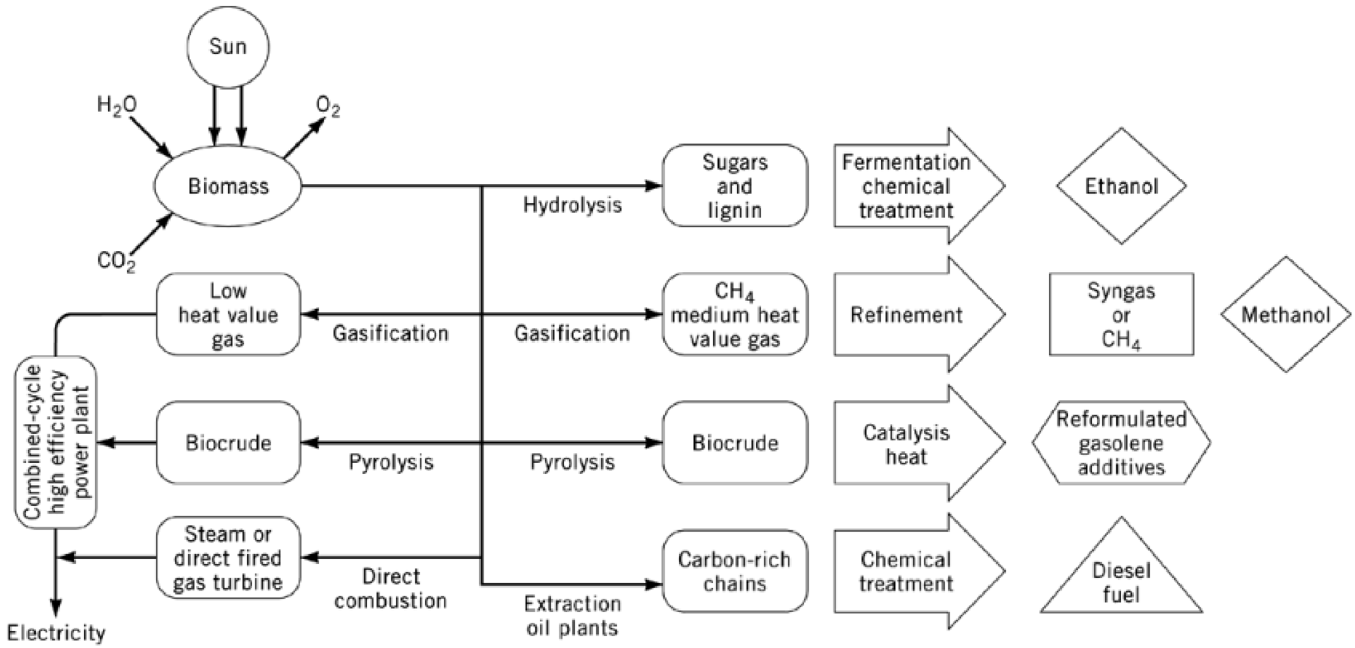

Fig. 7. Biofuels and biomass electricity production. Courtesy of the National Renewable Energy Laboratory.

electric power generation. The third is by gasification into a fuel used on the site. The fourth is by conversion into a liquid fuel that provides the portability needed for transportation and other mobile applications of energy. Figure 7 shows the varied pathways which can be followed to convert biomass feedstocks to useful fuels or electricity.

4.1. Thermal Combustion of Biomass

Direct combustion in air is the principal mechanism used to convert biomass into useful energy. The heat or steam (qv) produced is used to generate electricity or thermal requirements for industrial processes, building heating, cooking, or district heating in municipalities. The thermal combustion of biomass for cooking, space heating, or the production of process heat, either directly or in the form of steam, may be attractive where biofuels are available at economic prices or, particularly in rural areas, where the fuel may be available for gathering by the consumer. Small-scale use, such as for home cooking and fireplace use, has traditionally been inefficient.

Larger furnaces and boilers have been designed and are available for burning various types of biomass such as wood, wood wastes, chips, black liquor from pulping operations, food industry wastes, and MSW. The larger units can be very efficient, nearly matching the performance of fossil fuel furnaces. The greater moisture content of most biomass, as well as the wide range of particle size and composition, make it difficult to achieve comparable efficiencies at reasonable costs. The economic advantages, however, make installation of cogeneration facilities attractive for most industrial consumers having available biomass feedstock.

The residential sector uses biomass for direct applications such as cooking and space heating. Considerable progress has been made in the design of household cooking and heating appliances that use biomass, primarily wood, to improve efficiency and reduce CO and particulate emissions. Energy-efficient cooking appliances as well as heating equipment, such as stoves and fireplaces, have been developed, although costs and appearance of fireplace equipment, for example, have deterred use, particularly in potential retrofits. Restrictions on allowable emissions from the burning of wood or increased conventional energy prices could stimulate additional conversions of existing wood-fired installations and fossil-fueled or electric equipment.

The industrial sector uses biomass for both process and space heating, as well as power generation, often jointly in cogeneration projects. The technology available to these larger consumers, however, is equivalent to that used in burning conventional fossil fuels and has been widely implemented. Somewhat lower efficiency is obtained compared to fossil fuels as the result of the high moisture content of biomass. Moreover, derating of the furnace or boiler used might occur for a plant not designed with the flexibility to handle biomass. However, the lower efficiency of the combustion process is often more than offset by the low cost of the fuel, particularly if it is waste or by-product material that otherwise would be marked for disposal. The small amount of ash produced is usually suitable as a soil supplement.

4.2. Generation of Electric Power Using Biomass

As of this writing (1996), electric utilities were making only limited use of biomass as a fuel for power generation, although the utilities often bought power from cogenerators who used biomass as fuel. Most power generation from biomass, whether generated by industry or utilities, was via steam turbines. Research is continuing to develop gas clean-up technologies that would permit use of gasified biomass as a fuel for gas turbines. Wood and wood wastes and by-products are the principal fuels.

Electric power generation using biomass as a fuel is economic in situations where the cost of the fuel is competitive with that of fossil fuels. The cost of a commercially available biomass steam–electric power plant is about $1500/kW for a wood-fired facility. If wood can be obtained at a cost of $2.00/GJ ($\$2.10 \times 10^{-6}$/Btu), the total cost of power for base-load operation would be about $0.05/kWh. If wood or agricultural wastes are available at lower costs, the cost of electricity would be significantly lower. Similarly, if the low pressure steam from the turbine exhaust can be used (cogeneration), the overall efficiency would be higher and the costs would be lower.

Greater use of biomass resources (exclusive of MSW) in electricity generation is constrained by delivered resource costs. Wood or other biomass resources must generally be procured within no more than a 80-km radius of the power plant to be economical. Transportation costs for biomass are high. All generation capacity (other than MSW plants) has been sited where readily accessible waste resources are available at low cost. Biomass-fueled plants which are to be competitive with coal, oil, and natural gas, the fossil fuel feedstocks, must be available for $2.00/GJ or less, although a higher fuel cost may be competitive in isolated locations where low cost coal is not a viable alternative as a fuel source. At high levels of utilization, competition among energy and nonenergy uses may tend to bid up biomass resource prices. To stabilize price and availability, a potential long-term solution is the development of dedicated high productivity herbaceous or short-rotation woody crops for feedstock production.

4.3. Gasification of Biomass

The third energy conversion mechanism is the production of biogas, a mixture of methane and carbon dioxide, CO_2, which can be produced from either thermal conversion or the biological anaerobic digestion of biomass materials. The methane can be subsequently separated from the CO_2 using conventional technology and the resultant gas supplied to a natural gas system or other consumer. Processes have been developed and tested; some have been applied in commercial operations where biomass feedstocks were available at low cost. MSW may be processed anaerobically to produce methane from the digestible components. The volume of gasification residue, which includes materials such as burnable plastics, is greater than the residues from combustion processes. Combustible plastics and similar materials could be separated if required before feeding the remaining material to the digester. Landfills are also a source of methane produced from the decomposition of MSW although the economics of recovery of the naturally occurring methane are not universally favorable. A lower heat-content gas, syngas, consisting primarily of carbon monoxide and hydrogen (CO and H_2), can also be produced for use as a fuel or as an intermediate feedstock.

Interest in the development of a high efficiency biogas-fueled power plant has increased to the point that the Global Environmental Facility (an arm of the World Bank) has decided to fund a demonstration project in Brazil. The Biomass Integrated Gasification–Gas Turbine (BIG–GT) project is proposed to use trees from a eucalyptus plantation in the state of Bahia to demonstrate high efficiency biomass electricity technology with a 25–30-MW plant. The project team, composed of representatives of the Brazilian Ministry of Science and Technology, Electrobras and several of its regional utilities, and Shell Brazil, has decided to use a low pressure gasification technology developed by the Swedish company TPS. The BIG–GT technology could eventually achieve efficiencies on the order of 50% and promises to revolutionize the field of biomass electricity production.

4.4. Biofuels

Biofuels are liquid fuels, primarily used in transportation (qv), produced from biomass feedstocks. Identified liquid fuels and blending components include ethanol (qv), methanol (qv), and the ethers ethyl *t*-butyl ether (ETBE) and methyl *t*-butyl ether (MTBE), as well as synthetic gasoline, diesel, and jet fuels.

4.4.1. Ethanol

Ethanol can be produced from sugar (qv), starch (qv), or cellulosic feedstocks, ie, from wood, energy crops, and municipal and other wastes. In the United States, the primary pathway for conversion of biomass to alcohol fuels is the fermentation of corn to ethanol. In the biochemical conversion process, the biomass feedstock is first separated into its three main components, cellulose (qv), hemicellulose (qv), and lignin (qv). The cellulose is hydrolyzed to sugars, primarily glucose, which are then fermented easily to produce ethanol. The hemicellulose portion is more readily converted to sugars, primarily xylose; however, xylose is more difficult to ferment to ethanol. Finally, the lignin, although it cannot be fermented, can be converted to a high octane liquid fuel or, as is more common, burned to provide process energy.

The cost of ethanol produced from corn in the United States is about $0.34/L. The corn feedstock represents roughly half of this cost. Revenues from animal feed coproducts include about half the total costs. At this cost, ethanol production is not competitive with gasoline in the absence of federal and state tax credits. Laboratory research, utilizing biotechnology and genetic engineering, has reduced the estimated cost of cellulose-derived ethanol to about $0.36/L. Research plans, based on the use of enzymatic hydrolysis technology, suggest that a goal of $0.16/L may be achievable as early as 1998 for ethanol from cellulosic and hemicellulosic feedstocks. This cost would be competitive with the projected prices of gasoline without tax credits.

4.4.2. Methanol

Methanol is made from biomass by first gasifying the feedstock to form a syngas, a mixture of CO, H_2, CO_2, higher hydrocarbons, and tar. A gas shift reaction is employed to adjust the chemical structure of the components of the gas mixture to the requisite H_2-to-CO ratio. The syngas is then cleaned and conditioned before being converted, in the presence of standard commercial catalysts, to form methanol. Research, development, and demonstration have produced several gasifiers that make syngas. Biomass gasifiers are specifically designed to take advantage of the superior characteristics of biomass feedstocks as compared to coal, ie, very little sulfur, high volatility, greater hydrogen content, and low ash content, for the production of syngas.

Although biomass-to-methanol technology has yet to be commercialized, laboratory technology suggests that commercial production would be feasible at a cost of about $0.20/L. Assuming that expected improvements in syngas cleanup and a reduction in feedstock costs are realized, the costs may be reduced to the target of $0.15/L as early as 1998.

4.4.3. Synthetic Hydrocarbon Fuels

The basic approach used in converting biomass to traditional hydrocarbon fuels is to first pyrolyze the biomass feedstock to form an intermediate biocrude liquid product. The second step is to catalytically convert the biocrude to gasoline (see Fuels, synthetic). The technology uses a fast pyrolysis step that obtains higher yields of desired liquid components than those achieved in longer residence time processes. The fast pyrolysis process has been demonstrated using three different reactor designs. There are two potential routes for the second step: hydrogenation at high pressures and zeolite cracking at low pressures. As of the mid-1990s, attention is focusing on the potentially less costly, lower pressure process.

An alternative method of producing hydrocarbon fuels from biomass uses oils that are produced in certain plant seeds, such as rape seed, sunflowers, or oil palms, or from aquatic plants (see Soybeans and other oilseeds). Certain aquatic plants produce oils that can be extracted and upgraded to produce diesel fuel. The primary processing requirement is to isolate the hydrocarbon portion of the carbon chain that closely matches diesel fuel and modify its combustion characteristics by chemical processing.

Biomass-to-hydrocarbon fuel processes have yet to be commercialized. Based on research results, the cost estimate for the pyrolysis process is $0.42/L for gasoline. The cost target of $0.22/L by 2005 is based on expected achievement of improvements in the second-stage catalytic conversion process as well as the availability of feedstock at a cost of $2.00/GJ. At the mid-1990s stage of development of the technology, diesel fuel from algal oil was estimated to cost about $1.85/L. Process improvements and research accomplishments are needed to achieve the projected cost goal of $0.26/L by 2010. Substantial improvements in feedstock costs and in extraction technologies would be required in the same period to achieve similar cost reductions in recovering oil from algae or plant seeds.

BIBLIOGRAPHY

"Solar Energy" in *ECT* 3rd ed., Vol. 21, pp. 294–342, by D. Halacy, Solar Energy Research Institute.

Cited Publications

1. *Annual Energy Outlook 1994*, U.S. Department of Energy, Energy Information Administration, Washington, D.C., Jan. 1994.
2. C. Flavin, *Worldwatch*, Worldwatch Institute, Washington, D.C., Sept./Oct. 1996.
3. *A Pilot Golden Eagle Study in the Altamont Pass Wind Resource Area California*, National Renewable Energy Laboratory, Golden, Colo., NREL/TP-441-7821, May 1995.
4. C.-J. Winter, R. L. Sizmann, and L. L. Vant-Hull, *Solar Power Plants*, Springer-Verlag, Berlin, 1991.
5. R. B. Diver, in R. B. Diver, *Progress in Solar Energy Technologies and Applications: An Authoritative Review*, American Solar Energy Society, Boulder, Colo., Jan. 1994.
6. N. D. Becker, *Solar Today*, 24–26 (Jan./Feb. 1992).
7. G. Cook, L. Billman, and R. Adcock, *Photovoltaic Fundamentals*, DOE/CH10093-117-Rev 1, U.S. Department of Energy, Washington, D.C., Feb. 1995.

General References

8. K. W. Boer, *Advances in Solar Energy: An Annual Review of Research and Development*, Vol. **7**, American Solar Energy Society, Boulder, Colo., 1992.
9. *Renewing Our Energy Future*, Office of Technology Assessment, U.S. Congress, Washington, D.C., Sept. 1995.

10. K. Ahmed, *Renewable Energy Technologies: A Review of the Status and Costs of Selected Technologies*, World Bank Technical Page Number 240, Washington, D.C., Jan. 1994.
11. T. B. Johansson and co-workers, eds., *Renewable Energy—Sources for Fuels and Electricity*, Island Press, Washington, D.C., and Covelo, Calif., 1993.

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