SERI/TP-281-1846

SOLAR THERMAL CONVERSION

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November 1982

Prepared under Task No. 1430.76
WPA No. 153C-82

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Prepared for the
U.S. DEPARTMENT OF ENERGY
Contract No. EG-77-C-01-4042

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TITLE ABSTRACT

High temperature applications of solar energy for electricity and industrial process heat are being attained with solar power towers.

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*This article has been prepared for submission as an invited paper to American Scientist, which is published by Sigma Xi, The Scientific Research Society. Frank Kreith is currently a Sigma Xi lecturer.

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SOLAR THERMAL CONVERSION

Energy is not a good unto itself; it is valued rather as a means of satisfying important needs of a society. In classical thermodynamics, energy is defined as the capacity to do work; but from a more practical point of view, energy is the main stay of any industrial society. In the United States, energy is currently provided by seven primary sources: petroleum, natural gas, coal, hydro-power, nuclear fission, geothermal, and wood and waste. The first three of these sources are fossil fuels. They are stored forms of solar energy that received their solar input eons ago, have changed their characteristics over time, and now are in a highly concentrated and convenient form. It is apparent, however, that these stored forms of solar energy are being used so rapidly that they soon will be depleted. To maintain our present social structure, it is desirable, therefore, that we supply an increasing portion of our energy needs from renewable sources.

The radiative solar energy reaching the earth during each month is approximately equivalent to the entire world supply of fossil fuels. Thus, from a purely thermodynamic point of view, the global potential of solar energy is many times larger than the current energy use. However, many technical and economic problems must be solved before large-scale use of solar energy can occur. The future of solar power deployment depends on how we deal with these constraints, which include scientific and technological problems, marketing and financial limitations, and political and legislative actions including equitable taxation of renewable energy sources.

Approximately 30 percent of the solar energy impinging on the earth is reflected back into space. The remaining 70 percent, approximately 120,000 terawatts [1 terawatt is equal to 10^{12} watts], is absorbed by the earth and its atmosphere. Solar radiation reaching the earth consists of the beam radiation that casts a shadow and can be concentrated and the diffuse radiation that has been scattered along its path in space from sun to earth. The solar radiation reaching the earth degrades in several ways. Some of the radiation is directly absorbed as heat by the atmosphere, the ocean, and the ground. Another component produces atmospheric and oceanic circulation. A third component evaporates, circulates, and precipitates water in the hydrologic cycle. Finally, a very small fraction is captured by green plants and drives the photosynthetic process.

For solar energy to be used in meeting the demands of a society, it must be converted into heat, mechanical power, or electricity. The conversion methods can be divided into natural and technological conversion systems (see Figure 1). In natural conversion, the biosphere, i.e. earth, wind or water, serves as a solar energy collector and storage. Since no man-made collectors are needed, the cost of energy from natural systems is largely determined by the conversion equipment, such as a wind turbine. In technological conversion systems, solar energy must be absorbed by man-made structures or collectors; the amount of insolation intercepted is determined by the total area and orientation of the collecting surface at a given geographic location (Kreith and Kreider 1978).

The source of the sun's energy is a hydrogen-to-helium thermonuclear reaction. The outer layer of the sun, from which the solar radiation emanates, has an equivalent black body temperature of about 5760 K (5487°C). The solar energy reaching the earth, called insolation, is in the form of photons, or radiation, covering a range of wavelengths corresponding approximately to a 5760 K black body. To convert this radiation into useful energy, one may either use photons in the appropriate wavelength range of the spectrum to generate electricity directly by photovoltaic conversion devices; or one may use the thermal part of the radiation spectrum to heat a working fluid by thermal conversion in a solar collector. The following discussion is concerned only with solar thermal conversion systems.

The thermal conversion process of solar energy is based on well-known phenomena of heat transfer (Kreith 1976). In all thermal conversion processes, solar radiation is absorbed at the surface of a receiver, which contains or is in contact with flow passages through which a working fluid passes. As the receiver heats up, heat is transferred to the working fluid which may be air, water, oil, or a molten salt. The upper temperature that can be achieved in solar thermal conversion depends on the insolation, the degree to which the sunlight is concentrated, and the measures taken to reduce heat losses from the working fluid. Since the temperature level of the working fluid can be controlled by the velocity at which it is circulated, it is possible to match solar energy to the load requirements, not only according to the amount but also according to the temperature level, i.e., the quality of the energy required. In this manner, it is possible to design conversion systems that are optimized according to both the first and the second laws of thermodynamics.

The collection and conversion of the solar radiation to thermal energy depends on the collector design and the relative amounts of direct beam and diffuse radiation absorbed by the collector (Kreider and Kreith 1981). As indicated in the following discussion of solar thermal collectors, the collectors used for higher temperature applications can collect only the direct radiation from the sun. Figure 2 shows the annual average daily direct normal solar radiation for the contiguous United States, Alaska, and Hawaii; values range from under 2.78 $kW/hr/m^2$ (10 MJ/m^2) to over 7.22 $kW/hr/m^2$ (26 MJ/m^2) (Solar Energy Research Institute 1981). Peak direct solar radiation at noon during a clear day averages about 1 kW/m^2. Generally speaking, the southwestern and western regions of the country receive direct normal solar radiation levels sufficiently high for most high temperature solar thermal conversion applications.

High temperature heat is needed by industry for process heat and by utilities for electricity. In 1980, the last year for which statistics are available, industry and utilities accounted for approximately 73 percent of the 76.3 quads of energy consumed in the United States (Energy Information Administration 1980). The industrial process heat portion alone was 20.6 quads (17 percent). Figure 3 displays a recent analysis by the Solar Energy Research Institute (Krawiec et al 1981) of the distribution of industrial process heat requirements by process temperature. It can be seen that 48.9 percent of the process heat total falls below 500° F (260° C) and 34.0 percent is above 1000°F (538° C).

SOLAR THERMAL COLLECTORS

To be economically worthwhile, a solar collector must be selected to meet the needs of a given task. This is called end-use matching. From the time of solar architecture in ancient Greece over 2,500 years ago, many types of solar collectors have been developed. Several different collector types currently are in use for various applications, energy loads, and temperatures. These collector types include solar pond, flat-plate, evacuated-tube, line-focus, point-focus, and central receiver. Figure 4 shows the approximate operating temperature ranges for the collector types (Kutscher et al. 1982); brief descriptions follow.

Solar ponds are bodies of water that can simultaneously absorb and store solar energy. There are essentially two types: shallow ponds and salt gradient ponds. Shallow ponds consist of bags of water which are heated by the sun during the day and must be drained at night. Their upper level of temperature capability is 120° F (49° C), and their thermal efficiency is relatively low. Alternatively, salt gradient ponds can supply heat at temperatures up to 180° F (82° C) in favorable locations. The salt gradient pond consists of three "layers." The bottom or storage layer consists of a uniform high concentration salt water solution, while the top layer consists of a uniform salt water solution of low concentration. Between these two layers is the gradient layer in which the concentration increases with distance from the top. Heat losses from the storage layer are minimized because in the gradient layer the density is uniform and convection currents are suppressed. Therefore, solar radiation that penetrates to the bottom of the pond heats the storage layer from which thermal energy can be extracted, as needed.

The most common design for low temperature solar thermal conversion is the flat-plate collector. These collectors can supply hot water or hot air at temperatures up to 160° F (71° C) with relatively good efficiency. They require no moving parts, have good durability, and can collect both direct and diffuse radiation. A special variation on flat-plate collectors is the so-called evacuated-tube collector, in which the absorber pipe is surrounded by a vacuum to reduce thermal losses. These collectors can supply hot water up to 350° F (177° C) at good efficiency, but they are more expensive than ordinary flat-plate collectors. One of the most cost-effective applications of flat-plate collectors is domestic hot water heating. In Israel, over 2% of the total national energy demand is supplied by domestic hot water heating through flat-plate collectors.

The preceding collector types are limited to the lower temperature range for their applications. In order to achieve temperatures above 300° F (149° C), solar energy must be concentrated on the receiver. Concentration reduces the size and surface area of the solar receiver and, therefore, reduces the heat losses, which are proportional to the surface area. Higher concentration ratios thus give rise to proportional decreases in heat losses and allow higher temperatures to be attained. Concentration can be achieved by refraction (Fresnel lenses) or reflection (mirrors). Line-focus collectors which track the sun in one direction can achieve solar intensities of the order of 50 suns and deliver temperatures up to about 600° F (316° C). This tracking capability increases the complexity of the collector system. In addition, these concentrating collectors can only use the beam part of solar radiation. Compound parabolic concentrators (CPC) are an alternative design for line-focus collectors, but in practice they are only able to achieve a concentration ratio of about two (suns) without periodic adjustment.

In order to heat a fluid to temperatures above 1000° F (538° C) with good efficiency, it is necessary to achieve a concentration ratio of 200 or more. Such a ratio is possible only by means of dual-axis (azimuth and altitude) tracking of the sun with point-focus receivers. Basically two collector design approaches are available to obtain high solar concentrations: dual-axis-tracking paraboloid dishes with point-focus receivers, in which the reflector as well as the receiver move to track the sun; and stationary central receivers situated some distance above the ground, onto which solar radiation is reflected by tracking mirrors.

An array of tracking parabolic dishes can be arranged in a so-called distributed system so that the working fluid from each dish is piped to a central power conversion station. The disadvantage of this approach, however, is that heat losses between the receivers and the central conversion unit are high; also the complexity of flexible connections necessary between moving receivers and stationary piping reduces the reliability of such distributed systems. An alternative approach, also using tracking parabolic dishes, is to locate a heat engine that can generate electricity at the focal point of each dish and to transport electric current rather than a hot fluid. This approach has been used in a 100-kW electric power plant constructed in Kuwait by Messerschmitt—Bolkow—Blohm.

CENTRAL RECEIVER POWER TOWERS

The solar central receiver concept lacks many of the problems associated with point-focus receivers and is the favored approach to achieve high temperatures in large installations suitable for generating electric power or industrial process heat (Battleson 1981). Energy is transmitted as radiation to the central conversion device; therefore, thermal losses are reduced considerably compared to those incurred in transporting a high temperature fluid through an array of pipes. Figure 5 provides a simple schematic of the central receiver solar power tower concept. Dual-axis-tracking mirrors, called heliostats, concentrate the incident beam solar radiation and redirect it to a central receiver mounted on a tower, where it is used to heat a working fluid to high temperatures. The working fluid is piped to the bottom of the tower to be used as a high temperature industrial process heat source, converted to electric power, or stored for future use.

A system can be designed with heliostats either surrounding the tower or located to one side to avoid excessive shading of one heliostat by another. The total reflective area is limited to approximately 20 to 25 percent of the total land area. Typically, 70 percent of the solar beam radiation incident on the heliostats is then delivered to the receiver.

Each heliostat is composed of several individual mirror modules, a support structure, a drive and aiming mechanism, and a foundation (see Figure 6). Currently the most widely used mirrors are second-surface silvered, with structural backing using thin glass (1.5 to 3.0 mm thick) of low iron content to minimize the absorption of solar radiation in the dual pass to and from the mirror surface. Sizes of typical heliostats range from 40 to 60 m^2.

The receiver is a heat exchanger mounted on a tower. It is a critical component in the successful operation of the central receiver system. Many designs with different configurations and heat transport fluids have been developed and tested. The two basic approaches, shown schematically in Figure 7, are the external receiver and the cavity receiver designs. In an external receiver, the reflected solar radiation impinges on tubes through which the working fluid passes and that are arranged on the outside of a cylinder. In the cavity-type receiver, solar radiation impinges on the interior of a cavity lined with flow passages through which the heated working fluid passes. Working fluids for central receivers include water/steam, molten salt, liquid sodium, air, and helium.

The tower that supports the receiver can be made of steel or concrete. Steel towers similar to those used for oil derricks are typically used for smaller systems, whereas concrete towers similar to smoke stacks are more economical for larger systems. Solar central receiver towers must support more weight and accommodate different wind moments than smoke stacks or oil derricks, because of the mass and the cross sectional area of the receiver located at the top.

The other components associated with a solar electric power system, such as turbines, generators, pumps, valves, and heat exchangers, are similar to those commonly used in electric power or industrial plants and do not require special development.

Since insolation varies with time of day and time of year, the energy output of a central receiver systems also changes. The annual capacity factor, defined as the ratio of actual energy output to theoretical output for rated capacity operation all year, is about 30 percent in current designs. Higher end-use capacity factors require larger receivers and heliostat fields, as well as more thermal energy storage capacity. Since energy storage at high temperatures is both difficult and expensive, usually another heat source, such as a conventional fossil-fuel boiler, is currently used to supplement the solar thermal energy supply.

Solar One Power Tower

Application of the central receiver power tower technology for electric power production is exemplified by the Solar One Power Tower, a 10-W electric power pilot plant at Barstow, California. The Solar One project is funded jointly by the Department of Energy (DOE) and public utilities, with DOE providing $120 million and the utilities providing $21.5 million. The builders and operators are Southern California Edison, Los Angeles Department of Water and Power, and the California Energy Commission. The prime contractor for system design and integration is McDonald Douglas Astronautics. The turbine-generator facilities were designed and constructed by Southern California Edison, the boiler and the storage unit were manufactured by Rockwell International, and the heliostats were supplied by Martin Marietta Denver Aerospace.

The Solar One pilot plant applies the results of ten years of research and development to a solar-powered electrical generation plant. The primary objectives of the pilot plant are threefold: (1) to establish the technical feasibility of a solar thermal central receiver plant, including collecting data for industrial process heat and utility applications; (2) to obtain sufficient development, production, and operating data to indicate the potential for economical operation of commercial plants of similar design; and (3) to determine the environmental impact of solar thermal central receiver plants.

Solar One synchronized its turbo-electric generators on April 12, 1982, with the Southern California Edison grid and has operated continuously since that time. The plant, shown in Figure 8, is designed to produce at least 10 MW of electrical power to the utility grid (after supplying the plant parasitic power requirement) for a period of 4 hours on the plant "worst design day" (winter solstice) and for a period of 7.8 hours on the plant "best design day" (summer solstice). The "worst" and "best design days" are based on assumed insolation (solar intensity) conditions as derived from actual site insolation measurements. During plant operation, the plant capability and electrical output will depend on the insolation and atmospheric conditions. For certain periods of the year (near noon from March through September), the plant energy collection capability can exceed the 12.5 MW electric turbine-generator rating.

Each of the 1818 heliostats of Solar One has a mirror area of 40 m^2 that continuously reflects solar beam energy onto an external cylindrical boiler. The boiler, located atop a 76-m-tall tower, is 7 m in diameter and 12.5 m in height. The heliostat field occupies a land area of 0.3 km^2 (75 acres), simulating a large parabola with the boiler at the focal point. The system operates by circulating water through the receiver/boiler to generate steam, which is used to drive a conventional steam turbo-electric generator. The turbine inlet temperature for the steam from the boiler is 960°F (516°C) at 1450 psi (10 MPa). The plant uses a 4-hour oil and rock thermal storage system that enables it to operate at a capacity factor of 38 percent.

Since its start-up, Solar One has generated over 750,000 kWh. A daily record of 56,600 kWh was produced on May 19, 1982. In mid-July, weekend power production for transmission by the Southern California Edison grid to consumers was initiated. On October 10, 1982, during weekend operation, a new maximum net output of 10.4 MW electric was recorded (Bartel and Skvarna 1982). Solar One has already demonstrated that the central receiver concept works as expected. A five-year test program is now underway in which both systems testing and electrical power generation will be carried out. The first two years of the test program will be devoted to design verification of the individual components and systems and to demonstration of the various modes of operation. Additionally, controls will be updated so that the plant can be operated with a minimum operating staff, and the collector system will be integrated into the overall control system. During the last three years of the test program, electrical output will be maximized and plant reliability will be demonstrated.

ECONOMICS OF SOLAR POWER TOWERS

Solar power towers require a high initial capital investment, but they have low fuel costs. Nuclear and fossil-fuel plants have a much lower initial construction cost, but they require fuel that is heavily dependent on market pricing for their operation. Economic comparisons between a solar central receiver plant and a nuclear or fossil-fuel plant should, therefore, be made on the basis of the levelized costs of the energy produced, not on their respective initial construction costs. The levelized costing method distributes initial construction costs and fuel costs over the life of the system; it yields a levelized busbar price of energy, which is the price the consumer has to pay.

The heliostat field is the largest cost component of a solar central receiver plant. The capital cost associated with the installed heliostat, including foundation, wiring, controllers, and computers, ranges from 50 to 60 percent of the total system installed cost. This cost depends on whether the application is to produce electricity or process heat and on the unit price per heliostat (Thornton et al. 1980). The installed cost of the heliostats for Solar One was about $400/m^2 in 1980 dollars, based on the production run of 2000 heliostats. However, design improvements and production runs of 25,000 or more heliostats per year from a single manufacturer, are expected to reduce costs for second generation heliostats to the order of $110/m^2 in 1980 dollars (Sandia National Laboratories 1982).

According to some recent estimates, the total installed system cost for a second generation 100-W electric solar power plant is expected to fall in the range of $347 to $428 per kW thermal peak power, depending on the capacity factor (Hildebrandt and Gretz 1982).

Subsystem costs for a second generation plant with a 6-hour storage and 42 percent capacity factor are estimated at $97 million for the heliostats, $28 million for the receiver, $12 million for the thermal storage, and $41 million for the turbine-generator and miscellaneous equipment, for a total cost of $178 million.

A levelized cost comparison prepared by Martin Marietta Denver Aerospace of solar thermal central receivers with oil, coal, and nuclear power plants is presented in Figure 9. The two solid curves indicate the busbar energy costs, for heliostat costs of $\$107/m^2$ and $\$240/m^2$, as a function of percent capacity factors or hours of operation per year. The capital cost per kW electric of capacity and the fuel cost for the three conventional fuel power plants are also shown. It is clear from these data that solar power towers can only become cost competitive with other fuels when heliostat costs decrease to about $\$100/m^2$. A recent study conducted by the mass production experts of the General Motors Corporation (1979) projected an installed heliostat cost of $\$89/m^2$, if a production rate of 250,000 units per year could be achieved.

Researchers at the Jet Propulsion Laboratory have evaluated the effects of regional insolation differences upon advanced solar electric power plant performance and energy costs (Latta, Bowyer and Fujita 1981). The study projected both solar thermal power plant and conventional power plant energy costs for selected sites across the United States. The sites ranged from Barstow, California ($7.8\ kWh/m^2$ day) to Maynard, Massachusetts ($3.4\ kWh/m^2$ day). The levelized cost of electricity for central receiver (and other solar thermal conversion plants) were compared with projected costs for coal plants and for gas-turbine peaking plants. Solar power plants without storage systems are considered to be technologically equivalent to gas-turbine peaking facilities. The study concluded that central receiver plants (and paraboloidal-dish electric generation plants) will be cost competitive with residual-oil, gas-turbine peaking plants in many regions of the contiguous United States. The southwest sunbelt is the best location for central receiver plants to become cost competitive with fossil-fuel fired plants.

Another economic criterion used to compare solar power plants with conventional power plants is the energy amplification factor (EAF). EAF is defined as the useful-energy produced over the useful-life of the power plant divided by the capital energy required to construct the plant. Gretz (1982) has estimated the EAF for the heliostats of the European EURELIOS solar power tower (see later section for more information). Each of the 23-m^2 heliostats in the system produces electrical energy at about 25 kWh per day. On the basis of the specific energy inputs for the different materials of construction of a EURELIOS-MBB heliostat and their respective weights, an energy input of 14,150 kWh of energy was required to build the heliostat. Thus, this energy input would be amortized within 566 days of operation. This indicates that the energy payback is about two years. However, this figure is approximate because it compares "exergy" (electrical energy) output with energy input. The energy input for material production consists of both heat and electric energy; whereas the output of the system is electricity which is essentially pure "exergy." To produce 1 kilowatt-hour of electricity (or exergy) in conventional power plants requires the input of about 4 kWh of thermal energy.

FUTURE TECHNOLOGY DEVELOPMENTS

The Solar One central receiver power plant represents the first-generation system of technological components. The design and development of those first-generation components were begun in 1975. Starting in 1979, design and development of the second-generation components were initiated, including heliostats, receivers, and storage subsystems.

Second generation heliostats have now been developed and tested by four contractors for the U.S. Department of Energy. Although the four prototype heliostats are all of the same generic design, each contractor provided a unique approach to problems discovered in earlier heliostat designs. Modifications made at this stage eliminated inherent weaknesses of previous designs. In addition, the contractors' cost estimates for installed heliostats indicated that the heliostat cost goal ($80/$m^2$ in 1980 dollars) could be met after a few years of manufacturing experience.

Some completely new and novel concepts in heliostat design are now being developed at the Solar Energy Research Institute where a stretched membrane concept is being evolved and evaluated (Murphy and Sallis, in preparation). One major advantage of the stretched membrane concept is that it is a structurally efficient method of attaining and supporting a large optically accurate surface. By supporting the surface with tension, rather than with bending and shear as in normal cantilevered structures, more of the material can be worked to uniform stress levels resulting in both lightweight and low cost structures. Further, the stretched membrane can provide a reflective surface which tends to smooth out and attenuate surface irregularities emanating at the supports as well as other surface perturbations interior to the support periphery.

The primary goal of receiver technology development activities is to identify and develop those receiver concepts that are the most promising in terms of both function and performance (absorbing solar flux) and feasibility (as indicated by systems analyses). Secondary goals of the receiver program include reducing receiver weights and costs to practical limits; improving receiver efficiency by reducing the major thermal loss mechanisms; and developing receivers that are well integrated with the other plant components, thereby maximizing overall plant efficiency.

Receiver development work has concentrated on the molten nitrate salts and liquid sodium concepts. Molten salts and liquid sodium are replacements for water/steam as the heat transport fluid from the receiver to the turbine generator. Moreover, molten salt can be used economically for thermal storage. Thus, the receiver fluid can be stored without the expense or loss of thermodynamic availability associated with intermediate heat exchangers. In addition, molten salt receiver systems have broad application to electrical generation and industrial process heating, both with and without thermal storage. These new receiver technologies are under development by Martin Marietta Denver Aerospace, Babcock and Wilcox, Foster and Wheeler, and the Energy Systems Group of Rockwell International.

POWER TOWERS IN EUROPE AND JAPAN

Six new solar power towers for electrical power generation are under construction, installed, and/or operational in the United States, Spain, France, Italy and Japan. Solar One, already described, is in Barstow, California; the CESA-1 (Central Electrica Solar de Almeria) and the SSPS (Small Solar Power Systems) projects are both in Almeria, Spain; THEMIS (Thermo-Helio-Electrique-Megawatt) is in Targesoume, France; EURELIOS is in Adrano (Sicily), Italy; and Project Sunshine is located in Nio, Japan. Total power capacity of these six plants is 16-W electric.

CESA-1 is a 1.0-MW electric central receiver plant funded and built by the Centro de Estudios de la Energia and the Ministry de Industria y Energia of Spain. The collector field has a total reflecting surface area of 11,880 m^2; each of its 300 heliostats is approximately 40 m^2. The receiver uses water as the working fluid at an operating temperature of 977°F (525°C) and has an operating efficiency of 90 percent. Steam from the cavity receiver drives a Rankine-cycle turbine engine. Thermal storage is provided by a system using Hitec salt as the storage medium.

The SSPS project consists of two 500-kW electric solar thermal pilot plants, one central receiver and one distributed receiver, that are being built and operated at adjacent sites in Almeria, Spain by the International Energy Agency. Member nations participating in the SSPS project are Austria, Belgium, West Germany, Greece, Italy, Spain, Sweden, Switzerland, and the United States. The project's central receiver system employs a field of 93 heliostats having a total reflective surface area of 3655 m^2, a cavity receiver using sodium as the heat transfer fluid at an operating temperature of 986°F (530°C), a steam-driven piston engine coupled to a three-phase-current generator, and a hot tank/cold tank sodium storage system.

The 2.0 to 2.5-MW electric central receiver system of the THEMIS project uses a molten salt transfer fluid which is heated to 842°F (450°C) in a cavity-type receiver. Solar radiation is focused on the receiver by 201 heliostats, each with a mirrored surface area of 54 m^2. Molten salt enters the two-tank, five-hour storage system and is then fed through a steam generator to power a turbo-alternator connected to the French electrical distribution grid. Eleven parabolic dishes also installed at the site are used for trace heating Hitec and pre-heating water entering the steam generator. THEMIS is the first major effort undertaken by the Centre National de la Recherche Scientifique. It is funded jointly by the Agence Francaise pour la Maitrise de l'Energia (a governmental organization) and Electricite de France (the French national utility).

EURELIOS is a 1.0-MW electric (rated output) central receiver pilot plant that has been producing electricity since May of 1981. Funded by the Commission of the European Communities and built by a consortium of Italian, French, and West German industries, the plant has supplied a peak power of 0.75 MW of electricity to the Italian National Utility (ENEL) distribution grid. Heliostats of two sizes (23 m^2 and 52 m^2) are arranged in subfields beneath the cavity-type receiver, which is mounted on a 55-m-high tower. Steam exiting the receiver at 954°F (512°C) enters the steam turbine without going through an intermediate heat exchanger. Molten salt and hot water are used in the thermal storage system, which can provide 30 minutes of energy to smooth-out cloud transients.

Project Sunshine's central receiver plant in Nio, Japan began generating electricity in September 1981. It is one of many renewable energy efforts within the Sunshine project, being sponsored by the Japanese government, that together are expected to provide 7 percent of the country's energy needs by 1995. Construction of the 1.0-MW electric pilot plant was initiated in June 1978 by the Agency of Industrial Science and Technology, Ministry of International Trade and Industry. The water/steam central receiver plant was built by Mitsubishi Heavy Industries, Ltd., and features a field of 807 heliostats each 16 m^2 surrounding a conical-cavity receiver and steam drum on top of a 69-m-high tower. The receiver produces steam at roughly 482°F (250°C) and 580 psi (4 MPa) and enters the impulse turbine generator at a temperature of 369°F (187°C) and a flow rate of 7940 kg/h. The pressurized water thermal storage system provides the equivalent of 1-W electric power for 3 hours. At a direct normal radiation intensity of 0.75 kW/m^2, collector efficiency is 82.2 percent, receiver efficiency is 74.8 percent, and the turbine generator efficiency is 16.8 percent—for a total system efficiency of 10.3 percent.

ENVIRONMENTAL IMPACTS

Although energy created by solar power is one of the sources of energy being tapped for human use, solar-powered generating plants do have impacts on the surrounding environment. The environmental impacts are relatively small, but systematic baseline, construction phase, and operational phase studies are performed to ensure that man has knowledge of and control over any environmental changes.

Compared with conventional systems, solar power tower systems produce minimal air pollutants. In the short term, the SO_x and NO_x pollutants are reduced; in the long term, the CO_2 emissions are reduced and environmental quality is enhanced by decreases in the mining, drilling and transport of fossil fuels. Health and safety dangers appear minimal; none identified so far poses a major obstacle to accelerated solar power tower development. Furthermore, capital savings are effected because of the lower expenditures for pollution control technologies that are required to achieve a given standard of air quality.

The University of California at Los Angeles (UCLA) Laboratory of Biomedical and Environmental Sciences (LBES) is conducting the analytical studies for the Solar One project at Barstow. The first phase of the Solar One environmental effort has established the existing environmental conditions prior to breaking ground. This baseline report (University of California at Los Angeles 1979) focuses upon the soil, plants, animals, and micro-meteorology of the site and its periphery (as far as 3 km from the site). The pre-construction data for this report were gathered during 1978 and 1979. Rainfall, air temperature, chemical and physical properties of soil samples, seasonal changes in mean soil temperatures, displacement of surface soil, and attributes of vegetation were recorded, as well as the density and types of shrubs, insects, rodents, and animals. The baseline study will make it possible to determine the effect of the new facility on existing organisms.

The second phase of the study will monitor environmental changes during plant construction and operation and will manage revegetation. Vegetation management involves stabilizing soil surfaces adversely affected by power plant construction and operation.

LBES is also conducting studies, both in the field and in the laboratory, on the environmental and ecological effects of heat transfer and storage fluid spills. Spills have been staged at the Nevada Test Site in order to analyze toxicity as a function of soil type. LBES is currently performing lab tests on classes of compounds that are used or are candidates for heat transfer and storage fluids, such as hydrocarbons, silicon oils, and toluene. The laboratory is presently considering additional fluids for further testing.

Two additional environmental factors that are important to solar power tower plants in the 10- to 100-MW electric size range are the land and cooling water requirements. A solar power plant is land intensive because of the large area needed for the field of heliostats. Approximately 1.8 acres of land are required for each 1-W thermal of system design; for a 100-W electric power plant with a 40 percent capacity factor, 700 acres are required. Consequently, solar power tower plants are not going to be physically feasible in commercial or industrial areas where most of the land is already developed. In the southwestern United States, however, there are millions of areas of relatively unused land that are exposed to high solar insolation.

While the southwestern United States satisfies the land and insolation requirements for solar power towers, it lacks the water for evaporative cooling of the discharge fluid from the turbine generators of electrical plants. Water is a precious commodity in the arid and semi-arid parts of the western and southwestern parts of the country. Available water is used extensively for irrigation purposes and for municipal water supplies. Wet cooling is being used with the Solar One facility in Barstow, California, but future plants may have to be designed with the more expensive dry cooling system. Indeed, solar power towers designed with dry cooling and placed in the expansive desert land areas of the southwestern United States will have minimal environmental impacts and can produce much needed electricity for intermediate and peak load requirements of utility grids. In the long term they can also be used to generate hydrogen.

SUMMARY

Among the several solar thermal conversion technologies, solar power towers are on the verge of becoming a reliable source of electrical energy and high temperature industrial process heat. The central receiver technology is highly efficient, because it concentrates and converts direct solar radiation to heat a fluid to a high temperature which can be used for a variety of end uses. The cost effectiveness of the technology rests with the reduction in cost of heliostats by mass production. The overall technical and expected economic viability of solar power tower technology is attested to by the development and installation of systems all over the world. Furthermore, the U.S. Department of Energy and U.S. private companies are currently engaged in preliminary engineering design, bidding, and contracting for six additional solar power towers totaling 829 MW of power in California, Arizona, Hawaii, and Texas (Fausch 1982). Estimates for the capital investments in these facilities total approximately $2.8 billion.

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Figure 1. **Natural and Technological Solar Energy Conversion Systems.**

Figure 2. **Annual Average Daily Direct Normal Solar Radiation.**

Figure 3. **Distribution of Industrial Process Heat Requirements by Temperature.**

Figure 4. **Operating Temperatures for Various Types of Collectors.**

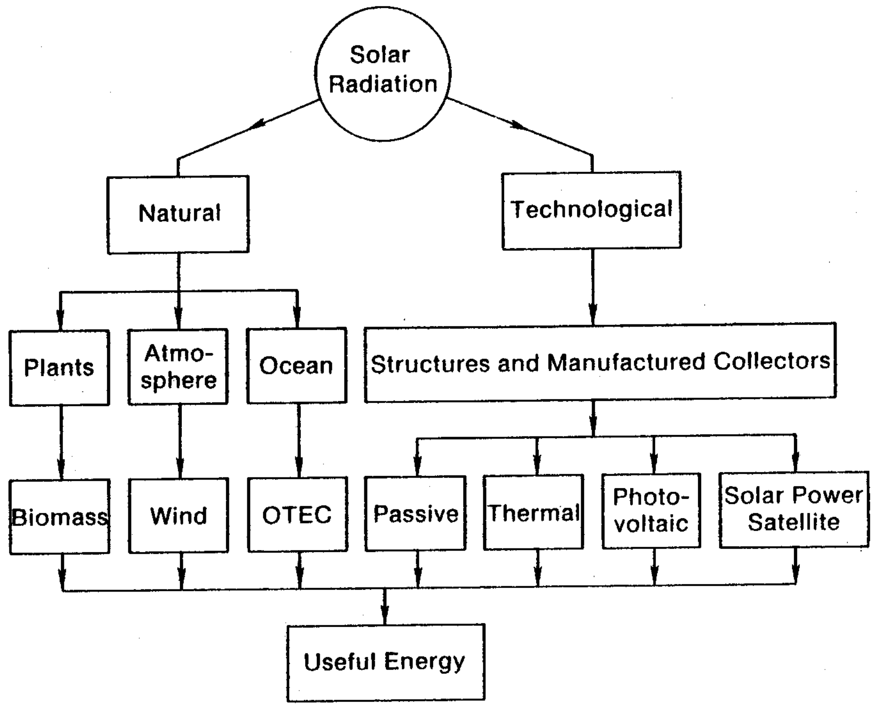
Figure 5. **Schematic of Solar Central Receiver Power Tower for Electrical Generation.**

Figure 6. **Heliostat for Central Receiver Technology** (Photograph courtesy of Southern California Edison).

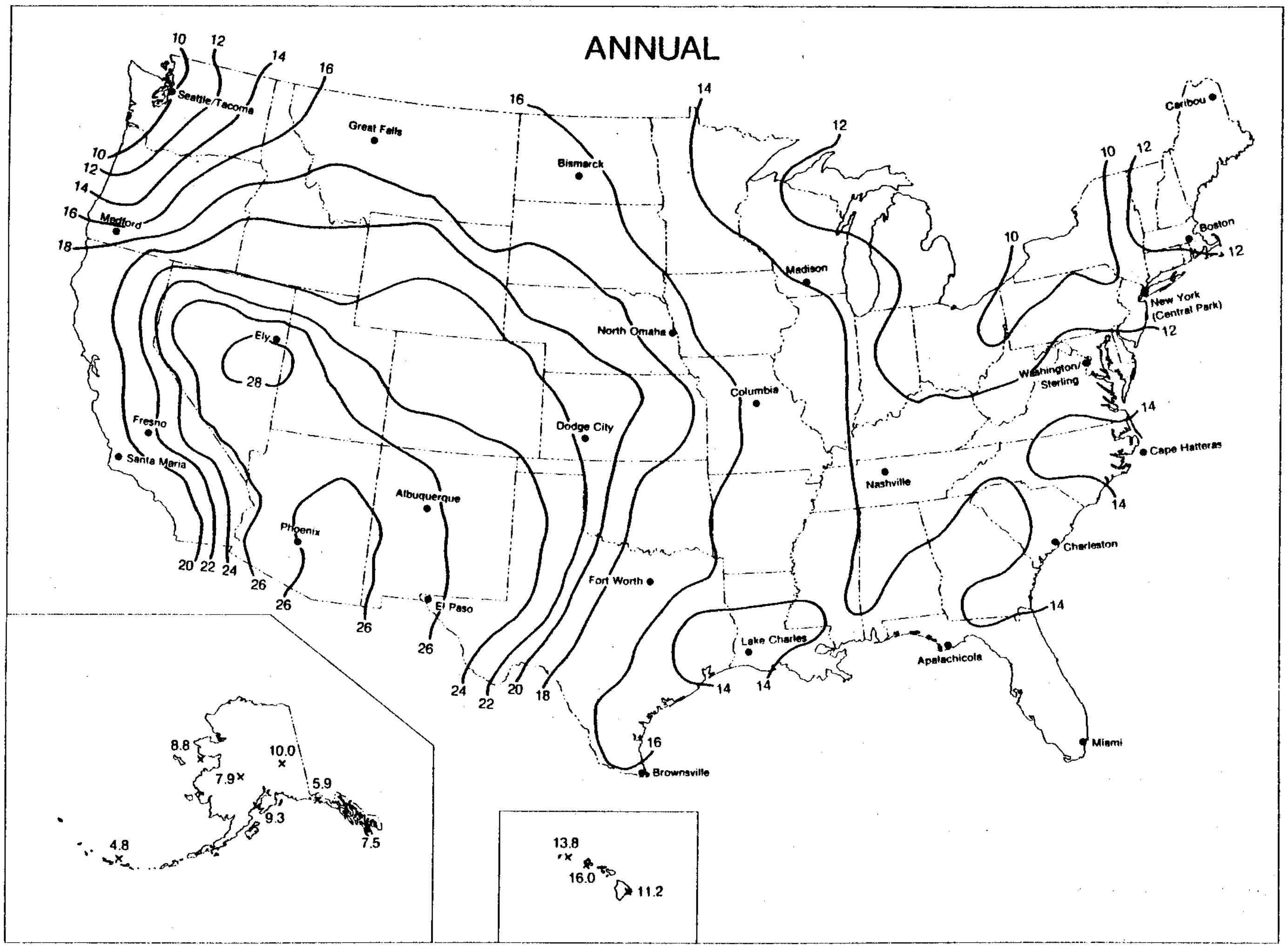
Figure 7. **Alternative Central Receiver Designs for Solar Power Towers.**

Figure 8. **Solar One 10 MW Electric Power Plant at Barstow, California** (Photograph courtesy of Sandia National Laboratories).

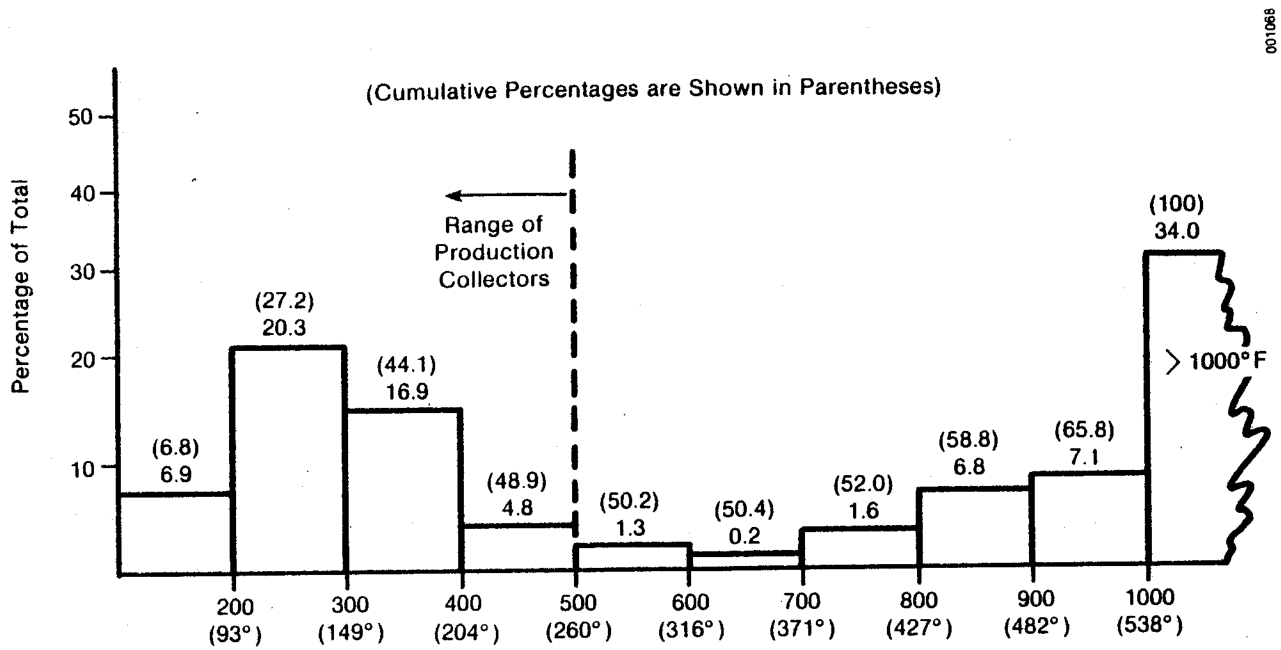
Figure 9. **Comparison of Levelized Busbar Energy Costs for Solar Central Receiver Plants with Oil, Coal, and Nuclear Fired Power Plants** (Illustration courtesy of Martin Marietta Denver Aerospace).



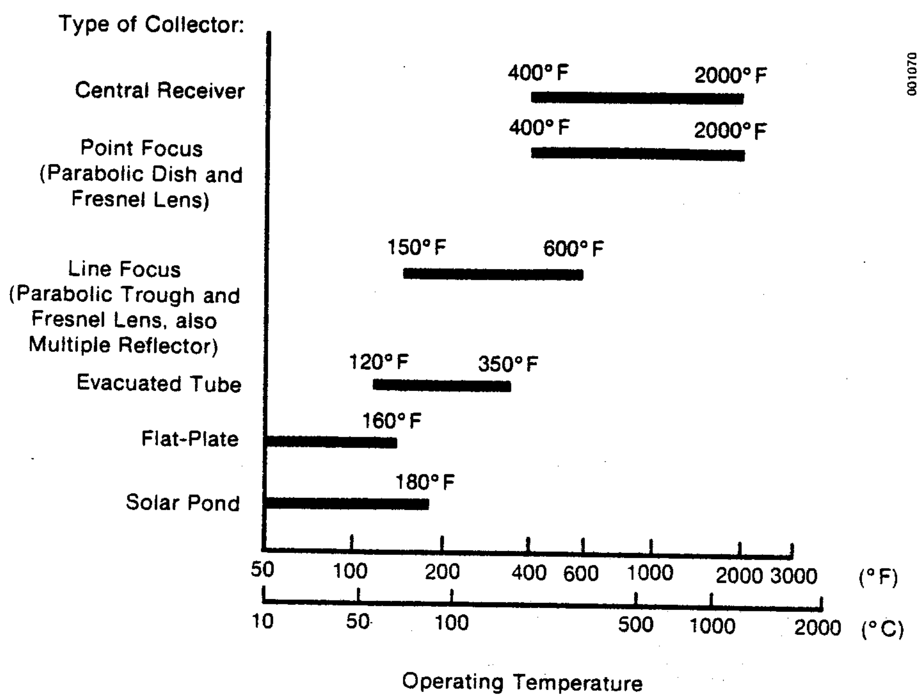
Solar Radiation
Natural
Technological
Plants
Atmo-sphere
Ocean
Structures and Manufactured Collectors
Biomass
Wind
OTEC
Passive
Thermal
Photo-voltaic
Solar Power Satellite
Useful Energy



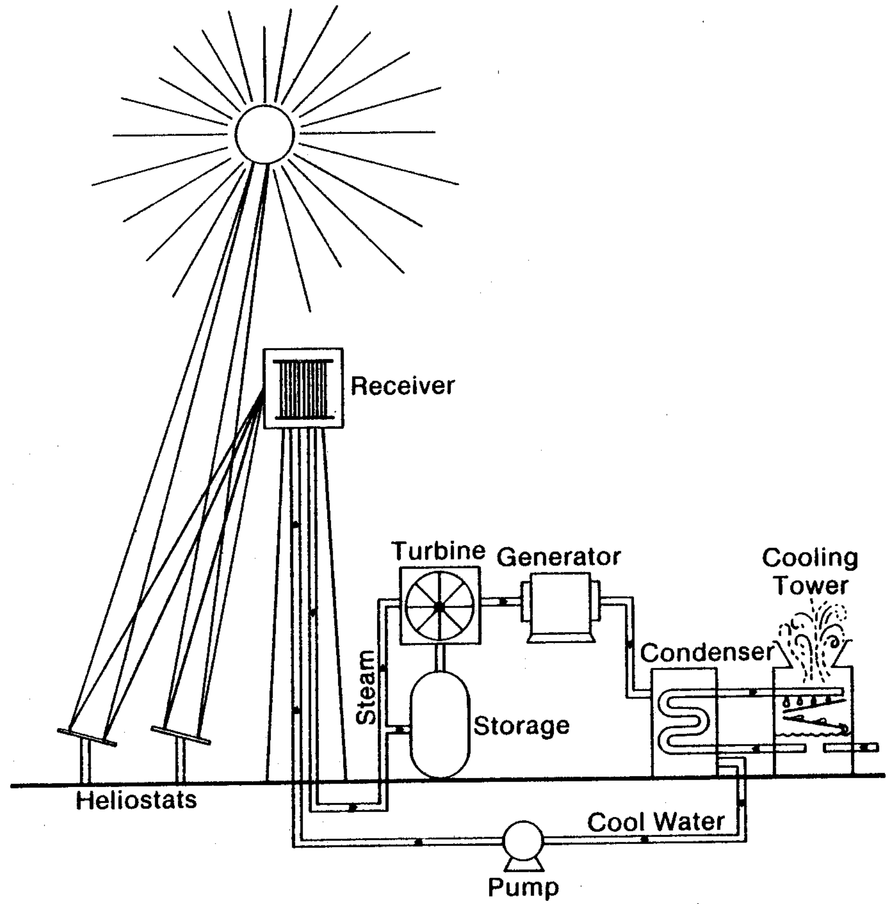
Annual Average Daily Direct Normal Solar Radiation (MJ/m²)

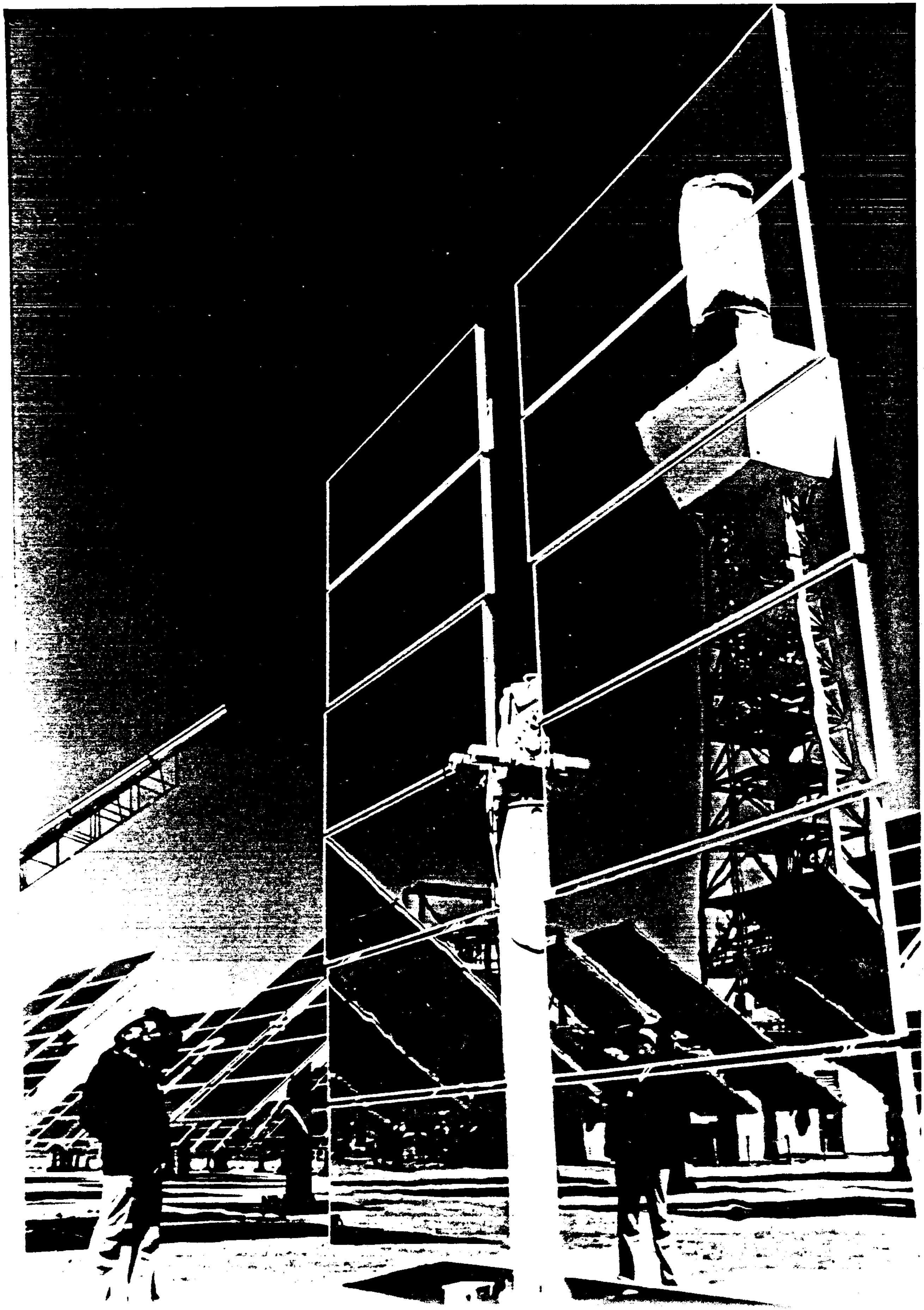


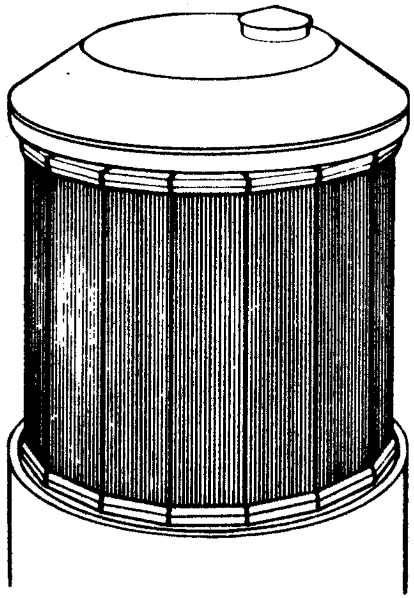
SOURCE: F. Krawiec et al., July 1981.



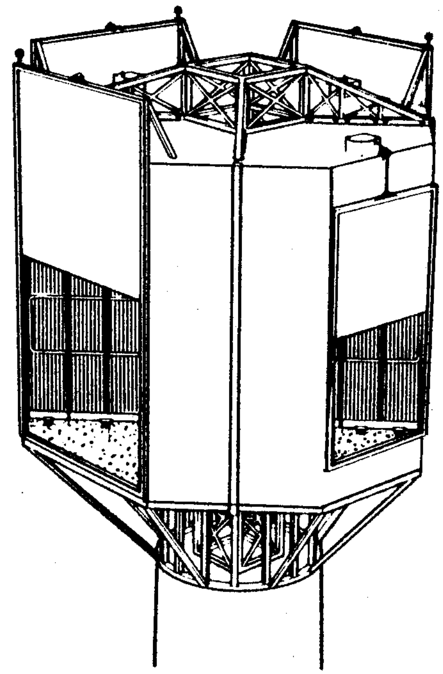
NOTE: Line-focus, evacuated-tube, and flat-plate collectors are commercially available; central receivers, point-focus collectors, and solar ponds are still being developed.


Receiver
Turbine
Generator
Cooling
Tower
Condenser
Steam
Storage
Heliostats
Cool Water
Pump

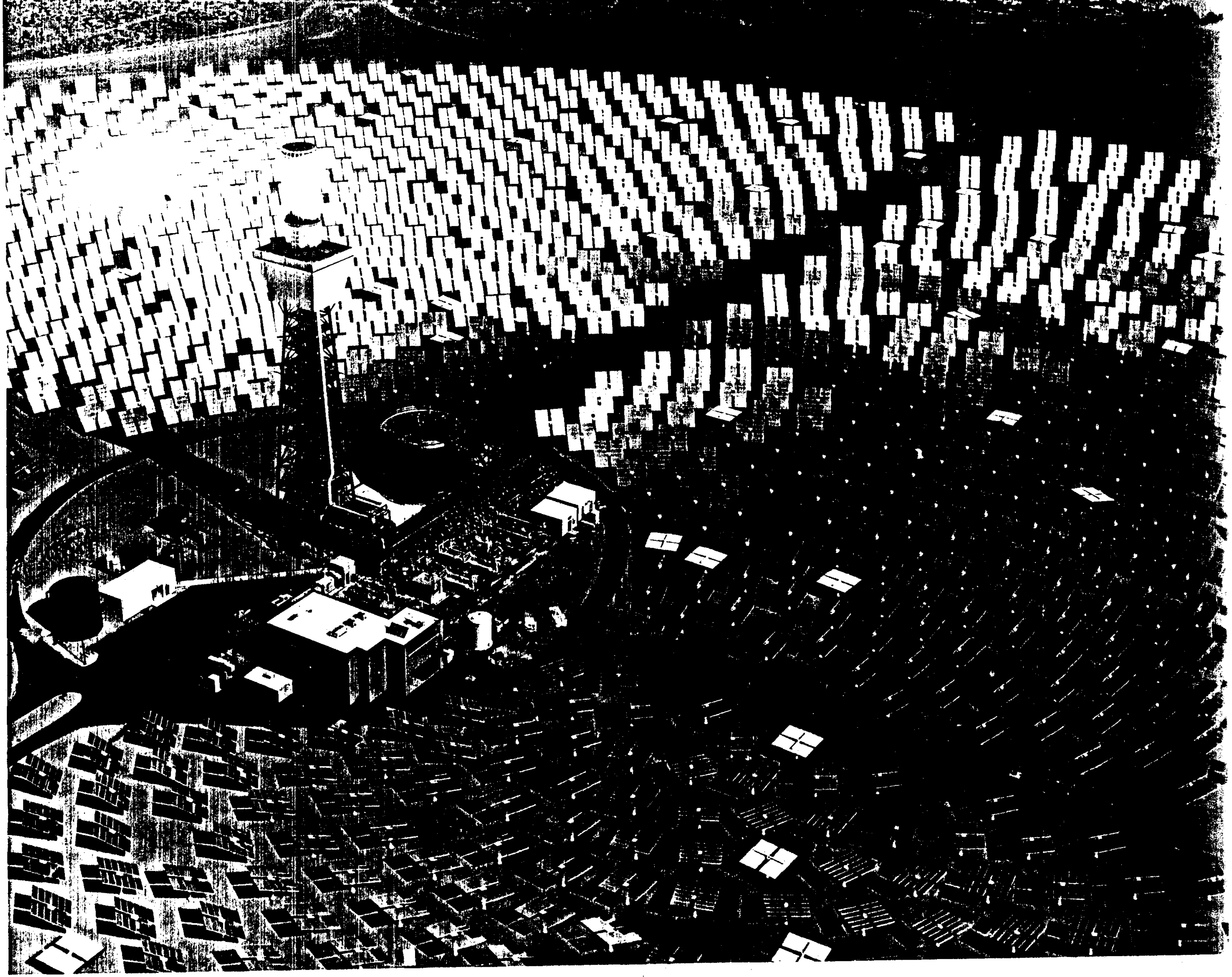


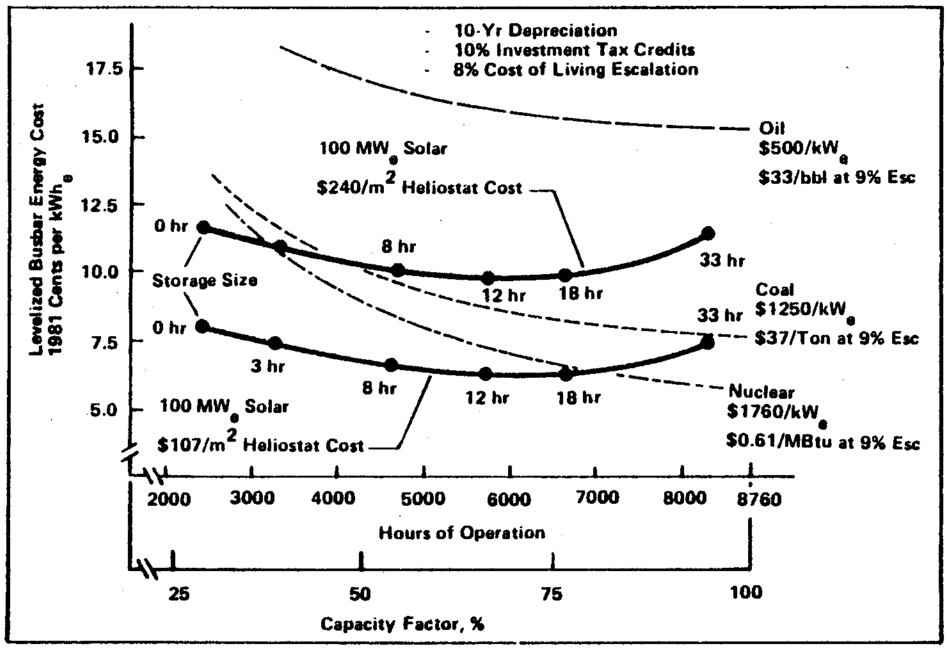


External Receiver



Multiple
Cavity Receiver




10-Yr Depreciation
10% Investment Tax Credits
8% Cost of Living Escalation
17.5
15.0
12.5
10.0
7.5
5.0
Levelized Busbar Energy Cost 1981 Cents per kWh$_e$
100 MW$_e$ Solar
$240/m^2 Heliostat Cost
0 hr
8 hr
12 hr
18 hr
33 hr
Storage Size
0 hr
3 hr
8 hr
12 hr
18 hr
33 hr
100 MW$_e$ Solar
$107/m^2 Heliostat Cost
Oil
$500/kW$_e$
$33/bbl at 9% Esc
Coal
$1250/kW$_e$
$37/Ton at 9% Esc
Nuclear
$1760/kW$_e$
$0.61/MBtu at 9% Esc
2000
3000
4000
5000
6000
7000
8000
8760
Hours of Operation
25
50
75
100
Capacity Factor, %