16 September 1977, Volume 197, Number 4309 SCIENCE

Power with Heliostats

A central receiver illuminated by a field of heliostats can absorb 10 to 100 megawatts of sunlight at 600° to 1000°K.

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Many solar collectors presently on the market are suitable for providing domestic hot water and for heating homes. The higher quality energy required to effectively drive an air-conditioning cycle is proving somewhat more difficult to obtain with flat-plate collectors, but promising solutions are on the horizon. There is a general consensus that further increases in energy costs or collector performance coupled with the cost reductions resulting from mass production will result in a sizable domestic market for solar collectors, and substantial reductions in fossil fuel requirements for residential heating and cooling over the next 10 to 20 years.

We would like to consider here a much larger potential market, the electric and gas utilities. Consideration of turbine cycle efficiency leads to the obvious conclusion that to generate electricity effectively high-quality heat is required, for example, 300°C and higher. Similar temperatures are required to drive most useful thermochemical reactions. Such temperatures are beyond the range of flat-plate collectors and are marginal for linear-focus, concentrating collectors. A further requirement of an electric utility is that individual units produce on the order of 100 megawatts of electricity. Smaller units tend to be less efficient and more costly to purchase and to operate. To power such a unit requires the use of most of the solar energy incident on 3 to 5 square kilometers. The use of 20,000 to 40,000 tracking parabolic dishes, each concentrating energy on an individual heat engine, is one relatively complex alternative. A second alternative is to collect the thermal energy from such a distributed array of linear- or point-focus concentrators by means of a fluid and use it to operate a turbine. The combination of costs and heat losses associated with such a heat transport system can easily become prohibitive. A third alternative is to collect energy optically from a large area with the use of heliostats.

Heliostats—large, nominally flat, two-axis tracking mirrors—can be used to hold the image of the sun (helio) stationary (stat) on an elevated absorbing receiver continuously. This procedure permits the absorption in a working fluid of about 2/3 of the flux incident (taken as the product of about 1 kilowatt per square meter penetrating the atmosphere multiplied by the total mirror area). Because of the central focusing of energy from thousands of heliostats, the absorbed energy can be extracted from the receiver and delivered to the ground at a temperature and pressure suitable for driving a conventional utility-type steam turbine for electrical generation. Three large design studies (discussed below), currently nearing completion, have shown no substantive technical problems with this approach. Cost estimates show that no dramatic technical breakthroughs should be required to bring the cost of this system, once it is in mass production, into the range where it can compete with other environmentally benign power plants.

In the balance of this article, we shall discuss (i) the plan of our solar thermal power system or "solar power tower" based on optical transmission, (ii) the history of the solar tower, (iii) the receiver subsystem, (iv) the design of the heliostats and their placement in a field, (v) thermal storage, (vi) environmental concerns, and (vii) economics.

The Plan of the Solar Tower System

A tower supporting a solar receiver-boiler is located near the center of a field of mirrors or heliostats (Fig. 1). Radiant energy reflected from the sun is intercepted by the receiver and absorbed as heat on its surface. High-pressure water circulating through tubes forming this surface is converted to steam and returned to the ground. Here it may be used to power a 100-megawatt (electric) turbine generator set and simultaneously to charge a thermal storage unit for deferred operation.

Although differing in detail, a variety of systems consisting of an external receiver (as shown in Fig. 1) or a cavity receiver can be designed to have an overall efficiency of 2/3 for the conversion of the energy incident on the optical aperture of the system into thermal energy (available as high-pressure steam), where the reference is the mirror area multiplied by a representative direct beam insolation of 950 watts per square meter. Typically, 20,000 heliostats each 40 square meters in area are arrayed over an area of 3.5 square kilometers surrounding a receiver elevated 260 meters above the ground to provide 100 megawatts (electric). Such a system can deliver an annual average of 5.5 kilowatt-hours of steam energy per square meter of mirror area on clear days in the deserts of the U.S. Southwest.

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History of the Solar Tower Concept

The concentration of the direct beam component of sunlight with heliostats was first attributed to Archimedes, who instructed soldiers to reflect the sun onto the sail of an enemy vessel by carefully orienting their burnished shields (heliostats). Their efforts were successful, for the vessel was set afire. It was not until several thousand years later that Trombe and his co-workers added hydraulically controlled servomechanisms to an array of large heliostats to produce an automatically controlled 1-megawatt (thermal) solar collector (*1*). Interested in producing high temperatures to melt materials, Trombe added a large, fixed concentrator consisting of a parabolic dish and achieved a temperature of 4100°K. Baum *et al.* (*2*) investigated a tracking array consisting of heliostats on moving railroad cars, aimed at an elevated cavity receiver-boiler. The cavity was to be rotated to face the heliostats throughout the day to achieve improved performance. They found that a prohibitive power requirement would arise because, at the very slow speeds involved, the wheels on the dusty railroad track would experience starting friction continuously.

Francia developed an intricate clock-driven field of 271 heliostats and was able to produce steam at a rate equivalent to 150 kilowatts (*3*). Using flat mirrors, he obtained an intensity somewhat less than 271 times the local beam component of direct sunlight, and with dished mirrors somewhat more. This concept is not suited for large-scale utilization of solar energy on a megawatt (electric) basis because it is impractical to connect many thousands of heliostats into a single clockwork device with sufficient precision. Moreover, the mechanism is not well suited to the larger mirrors required for an economical system design.

A reinvention involving a large number of heliostats took place in 1970–1971 at the University of Houston (*4*). [This work was supported by the RANN program of the National Science Foundation (NSF) beginning in 1973, and in 1975 it was transferred to ERDA (Energy Research and Development Administration) along with related investigations (*5*).] During our study of long-term problems in science and engineering, it became apparent that the outlook for energy sources beyond fossil fuels was hopeful but uncertain. Clearly, solar energy could be utilized. Since some investigation of the possibilities had already been carried out, we considered only the most promising options. Photovoltaic cells were considered first but, because of their large cost and low efficiency at that time, were rejected in favor of potentially efficient thermal conversion cycles compatible with the utility grids. Steam-electric conversion cycles producing 100 to 300 megawatts (electric) are well developed by the utilities, which also have a large-scale distribution system. It seemed advisable to utilize available transmission methods.

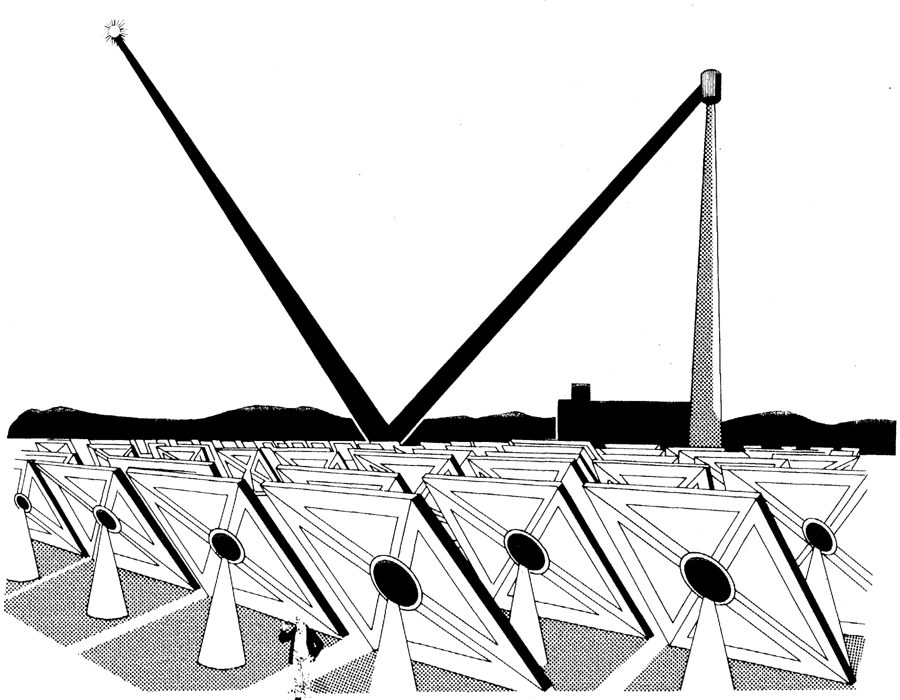

Fig. 1. The 100-megawatt (electric) heliostat power plant concept. The tower (260 meters high) near the center of the field has a boiler on top. About 20,000 heliostats (6.4 by 6.4 meters) would be required, spread over an area of about 3.5 square kilometers. A 10-megawatt (electric) pilot plant is under development by ERDA. Water is pumped up to the receiver and the steam is brought down to the conventional steam-electric generator usually employed by utilities.

The laws of physics tell us that the highest quality solar energy is obtained with a point-focusing device and that the radiative equilibrium temperature is limited to that of the source, in this case the sun at about 5720°K. To approach this temperature would require an ideal lens or a perfect-focusing mirror. Because large lenses require excessive bulk material, mirrors are preferable. Although many small focusing parabolas can be used, it is expensive to produce accurately curved mirror surfaces, and the required heat transport system entails substantial loss. Less loss would result if, using essentially flat mirror segments, we could have a single parabola with an aperture of about a square mile (2.6 square kilometers). In the 1950's Pilkington Brothers, Ltd., developed an economic process for casting precision flat glass by slowly cooling a continuous sheet of molten glass while floating it on a bed of molten tin (*6*). The resulting strips of float glass, 3 to 4 meters wide, can be used to construct large, two-axis steered mirrors or heliostats as depicted in Fig. 1. An array of these heliostats constitutes what might be described as a tracking Fresnel reflector.

In discussions of the solar tower concept, the question of the "best" size system always arises. The correct answer to this question depends upon the assumptions made or requirements imposed at the onset. For example, one may assume focusing optics with the total of aberrations and other optical errors fixed at some design value. Typically, a standard deviation of 0.166° or 3 milliradians can be achieved at moderate cost (the solar disk subtends about 10 milliradians). For such a system the concentration is fixed by the rim angle of the collector and the geometry of the receiver and will not be affected by scale. Thus, one is then free to choose the "best" system based on thermodynamic cycle efficiency and the economics of producing the selected collector, receiver, and energy transport system.

A capacity of 30 to 100 megawatts (electric) at a single site is probably as small as the utilities would like to consider integrating into the grid because of synchronization, switching, and dispatching problems. One can generate this electricity with a single turbine, using energy from a field with an area of 1 square mile collected either optically (solar tower) or by means of a heat transport system to gather to a common point the energy absorbed by a distributed system of collectors. The distributed system of collectors may consist of either numerous minitowers or a multitude of individual collectors. As an alternative to this heat transport system, one can use either small turbines with each small distributed field or minitower or very small engines at the focus of parabolic dishes. We believe that these alternate approaches will be less efficient and less economical than the single tower approach. Heat losses in the smaller scale systems are much harder to deal with, and smaller heat engines currently available are appreciably less efficient than the large utility turbines. In addition, the parts associated with each reflector unit are markedly increased in number and complexity if one adds a small heat engine to each one, such as a Stirling, or Ericsson, cycle isothermal expansion and compression engine. The shorter focal length of the smaller systems also makes it necessary to use a larger number of more highly curved reflector segments to achieve the required 3-milliradian beam error including aberrations.

The choice between one or a few solar towers is less sharp. The cost of towers up to about 350 meters in height tends to scale with the corresponding collector area, becoming appreciably more expensive in the 400-meter range. Below 200 megawatts (electric) the tower cost does not significantly affect the argument. In the range from 10 to 200 megawatts (electric), suitable steam turbine generator costs and thermal-to-electric conversion efficiencies favor the larger sizes. A 10-megawatt (electric) generator would cost approximately $300 per kilowatt (electric) and have an efficiency of 35 percent, whereas the corresponding values at 100 megawatts (electric) are $250 and 40 percent. Consequently, under the stated assumptions we would conclude that central receivers in the range from 50 to 200 megawatts (electric) are the most economical way to supply solar energy to an electrical grid.

This conclusion is reinforced by the fact that mirrors with a radius of curvature greater than a few hundred meters can be either stress-curved from flat sections or simulated adequately by a small number of facets, each canted at the appropriate angle. Either of these approaches is sure to be cheaper than casting self-supporting curved mirror segments of adequate optical quality to guarantee a high fraction of undistorted, specular reflection. For larger scale systems in the 50- to 200-megawatt (electric) range, the allowed segment size becomes equal to the 6-meter diameter of an economical heliostat, and nominally flat mirrors can be used. Removing the requirement for focus or canting segments relaxes a constraint on the heliostat design that will inevitably lead to lower cost heliostats and, consequently, a lower cost system.

For applications where a smaller amount of power is required at a local site, for example, a process heat or pumping requirement, other considerations come into play as well, such as the availability of a grid tie-in and the availability or requirement for reliable backup. Smaller units with a lower optical concentration will usually require lower operating temperatures to reduce convection and reradiation losses. In general, we believe that a single solar tower will be the most efficient, lowest cost, and most reliable means of supplying any solar requirement in the range from 1 to 1000 megawatts (thermal). Below 1 megawatt (thermal) a few parabolic dishes or troughs may be competitive. The only systems currently under development which may compete with the solar tower are the fixed reflector–moving receiver concepts. Although these are linear systems and so tend to provide lower concentration than is available with the "point focus" solar tower concept, these systems have the advantage of an emplaced reflector which does not require support or steering. After this advantage has been weighed against the disadvantage of a tracking receiver and relatively poor aperture utilization, a definitive comparison can, perhaps, be made. Because the reflector contour must be carved in the ground, individual collectors larger than a few megawatts are not practical. Thus for larger power requirements, the earlier arguments against distributed systems apply.

Aspects of the solar tower system—external or cavity receiver, flat or focusing heliostats, and methods of storage—are under study by a four-team ERDA effort to result in a preliminary design for a 10-megawatt (electric) pilot plant by June 1977 (*7*). Barstow, California, has been selected as the site for the pilot plant. It is anticipated that the first step in bringing costs for commercial solar plants into the range experienced for the construction and fueling of nuclear plants will be to increase plant size to at least 100 megawatts (electric) at a single site to achieve better collector and turbine efficiency. Figure 1 depicts the concept for a 100-megawatt (electric) demonstration plant (*7a*).

Other solar tower developments include pilot plants planned by the Electric Power Research Institute as well as the French and Japanese governments. An ERDA-funded Solar Thermal Test Facility (STTF) is under construction at Sandia Laboratory, Albuquerque, New Mexico, and is scheduled for completion in early 1978. The STTF is a small 5-megawatt (thermal) solar tower collector for testing the 10-megawatt (electric) pilot plant prototype components and performing related solar energy research.

The Design of the Heliostat Field

Because the heliostat field comprises about 50 percent of the total cost of a commercial solar tower system, design is crucial. For the 10-megawatt (electric) pilot plant there would be approximately 2000 heliostats, and for a 100-megawatt (electric) demonstration plant about 20,000 heliostats. The four design teams have all concluded that the most economical heliostats have an area of about 40 square meters and are composed of up to nine segments. For the pilot plant, the segments must be either curved or canted to provide an added degree of focusing. Important design factors are wind and gravity loading. The elevation and azimuth sensors and actuators must have a long life and will require only a fraction of a percent of the energy collected. The design should be suitable for mass production and easy installation.

The heliostats must be spaced in such a way as to avoid excessive shading of one another or blocking of the reflected radiation in the daily and yearly operation. Detailed computer analysis has shown that this can be accomplished for a nonuniform mirror distribution resulting in a ratio of reflector area to land area, ϕ, varying from 0.4 to 0.1 and averaging about 0.25. Far from the tower the heliostats must be sparsely distributed to prevent blocking of the reflected sunlight by adjacent heliostats. The heliostats are individually servo-controlled by a closed-loop sensor feedback system or by an open-loop computer control to reflect the solar beam onto the receiver all day.

A computer override initiates operation each morning and stow (shutdown) each night, sustains a uniform track in the event of a brief cloud interruption, initiates a rapid scram (shutdown) mode in case of coolant or boiler failure, or directs the heliostats to a safe orientation in case of adverse, inclement weather conditions. A vertical stow (orientation of the heliostat in a vertical position) can minimize hail damage or counter ice loading and, if the heliostats are facing downwind, can alleviate damage from blowing sand. A horizontal stow reduces structural specifications for surviving high winds, whereas a partially or totally inverted stow reduces the accumulation of dust. The heliostats are designed to withstand wind gusts to 170 kilometers per hour in horizontal stow. The possible requirement of an inverted stow is still under study and could add approximately 10 to 15 percent to the energy costs because of structural requirements in the heliostat mount and frame. A typical heliostat with sensor is shown in the far left of Fig. 2.

A map of the estimated direct annual beam radiation over the United States (Fig. 3) suggests why solar tower plants, as outlined, would be primarily situated in the desert Southwest. The heliostat system approximates a point-focus parabola and requires direct-beam radiation for imaging. The clear, dry, usually dust-free desert air ideally meets this requirement. As the solar elevation decreases, absorption due to the atmosphere increases; a useful number for the solar intensity when the sun is high overhead in clear days is 950 watts per square meter on a surface perpendicular to the rays. This is to be compared to about 1.35 kilowatts per square meter above the atmosphere.

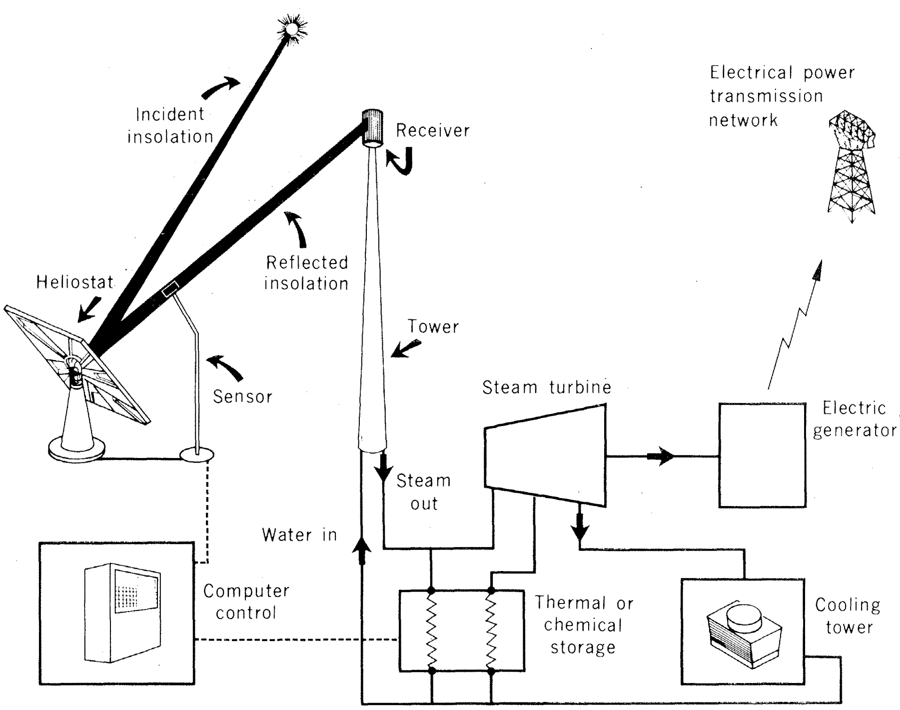

Fig. 2. Solar tower steam-electric power plant schematic. About 2000 heliostats would be required for the 10-megawatt (electric) pilot plant.

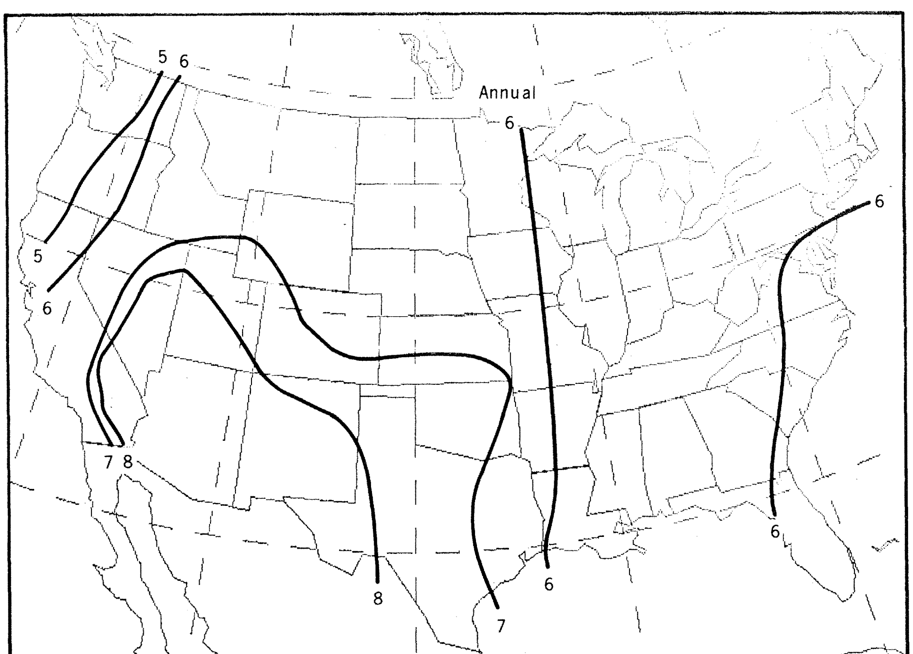

Fig. 3. Annual average direct-normal insolation (in kilowatt-hours per square meter) estimated from total hemispheric insolation (*17*).

Using a clear-air insolation model for an optimized heliostat layout, we obtain daily power curves as shown in Fig. 4 for flat ground at 35°N. However, favorable south slopes should be utilized where available. These calculations account for optical and thermal losses for a 100-megawatt (electric) generating plant with 6 hours of storage. While shading of heliostats and blocking of the reflected radiation is accounted for, losses can be kept negligible for solar elevations greater than about 25° by careful field layout. The mirror reflectivity is assumed to be 0.91 and the receiver absorptivity 0.95. Dust losses (5 percent) and radiation and convection losses (7 percent of the peak value) are also accounted for. The amount of energy transmitted into the working fluid varies with solar elevation from 2/3 to about 1/2 of the product of the solar intensity and the total area of the mirrors.

The Receiver

The receiver subsystem must be able to effectively intercept the sunlight reflected from the heliostat field and absorb it as heat. The heat must be transferred to the receiver coolant at the desired temperature with minimal loss due to reradiation and convection. For a 100-megawatt (electric) commercial receiver we have determined that these requirements can be met effectively by a cylindrical receiver 17 meters in diameter and 25.5 meters tall, supported 230 to 300 meters above the heliostat field. The outside cylindrical wall forms the absorbing surface, which is made of 24 identical panels each 2.2 meters wide. For a water-steam receiver each panel will be composed of 170 Incoloy-800 tubes 13 millimeters in outside diameter connected to headers or manifolds at the top and bottom. The water will be transformed to superheated steam in a single pass through the receiver. The flow of preheated coolant through each panel will be independently controlled to compensate for variations in incident flux. Consequently, the output from all panels can be combined into a single downcomer. With normal design and insulation, the heat loss of this energy transport subsystem is insignificant. For the external receiver using water-steam as a working fluid, the outlet temperature is between 500° and 550°C. At this peak temperature a perfect blackbody can radiate only about 25 kilowatts per square meter, and convection losses, even in a strong wind, are only about half as great, for a maximum loss of less than 40 kilowatts per square meter. For the steam system the receiver flux will be reduced by a multipoint aim strategy in the pilot plant to about 300 kilowatts per square meter (600 in the commercial design). In each case the average flux (and mean loss) is about 2/3 the quoted value, so that the respective receiver losses are about 12 and 6 percent, respectively. The higher receiver temperatures tolerated in a receiver cooled with liquid sodium we have considered might double the thermal loss per square meter, but, since fluxes of up to 2 megawatts per square meter can be tolerated, a smaller receiver can be used so that the percentage loss would, in fact, be less.

A variety of cavity designs are under study as alternatives to the external receiver we describe here. These include tube type, multiple-pass, water-steam boilers; open-cycle air or closed-cycle helium ceramic tube or honeycomb surfaces; and cavities incorporating direct absorption in a molten salt flowing over the inner wall of the cavity. Although the cavities are likely to provide lower thermal losses, we prefer the external design for five basic reasons. (i) It has a very wide acceptance angle and so has less influence on the design of the heliostat field, the largest cost item in the entire system. The area of the cavity aperture, which radiates as a blackbody, must be kept small to retain any advantage. The acceptance cone half angle, θ, is therefore restricted to about 60° because the required radius of the aperture is (R/ cos θ), where R is the radius of the extreme beam. (ii) The cavity must be supported and insulated on its exterior surface. This exterior structure is substantially more massive than the interior support structure of the external receiver. (iii) Any one of the 24 modular panels of the external receiver can be replaced overnight, whereas the cavity would have to be serviced and repaired in situ. (iv) It is easy to design minimal constraint supports and structures for the exterior receiver panels, whereas the added complexity of the cavity boiler designs for the steam system tends to constrain the tubing, leading to excessive thermal stresses. (v) The lightweight components of the external receiver can more readily follow the variations in insolation due to clouds and other adverse weather conditions.

The Tower

For a 100-megawatt (electric) system our analysis of the most cost-effective collector field geometry shows that the receiver must be elevated 260 meters above a field of heliostats with an area of 3.5 square kilometers. To support the considerable weight of the receiver and its steel support structure as well as the thermal transport system, we have chosen a tapered cylindrical-shell, slip-cast concrete structure. Inasmuch as this structure is designed to survive probable seismic disturbances in the West, it is sufficiently rigid to restrain sway of the receiver to less than 0.3 meter in winds occurring while the heliostats are operating. Sites near major seismic faults should be avoided because of the accompanying increase in the costs of the tower and heliostat supports. For most of the southwestern United States we have used a tower cost of $8 million.

Storage

Opponents of solar power insist that the solar tower concept should provide reliable power on cloudy days and also meet the nighttime baseload requirements. We believe that both of these requirements are unreasonable, at least in the early stages of development. Because thermal storage for cloudy days would be used only occasionally, the cost per cycle would be prohibitive. Although the storage system to provide for overnight operation would be used every day, the baseload application is the least competitive first use of solar energy. The market value of baseload electrical power is about half that of load-following power, that is, power that is generated to meet intermittent high demands, usually during the hours of 10 a.m. to 8 p.m. The electrical load parallels the solar supply (with a 2- to 4-hour delay); therefore, the most attractive first application is a plant designed for load-following with storage for 4 to 6 hours of operation to provide stable operation and to better match the observed utility load. A gas turbine plant with a low capital cost and a relatively high fuel cost can be added to the grid to supply the intermediate load power on the rare cloudy days when electrical demand is high.

The amount of thermal storage incorporated in the current design effort is sufficient to operate the turbogenerator for about 6 hours. This will permit penetration of the intermediate-to-peak-load utility market which usually occurs in the evening. Capacity credit will accrue to such a plant, and the storage will provide a cost-effective way of handling solar insolation differences in summer and winter. In the winter, a plant may be in the on-line, standby mode in the mornings so that the storage can be fully charged for evening operation, whereas

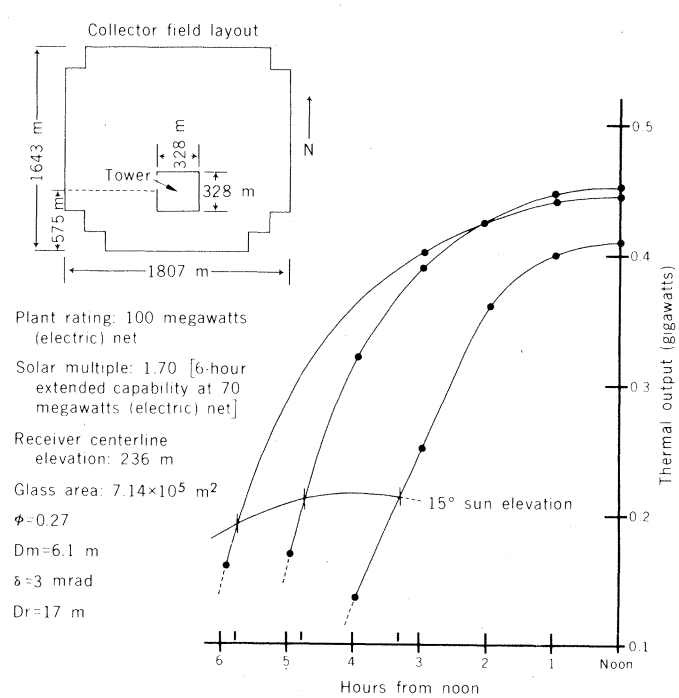

Fig. 4. Diurnal power curves for the field shown in the inset at 35°N. This field, coupled with 6 hours of thermal storage, would supply a 100-megawatt (electric) steam-electric generator. The thermal output, in 10^9 watts, is that deposited in the working fluid and includes loss estimates of 9 percent for reflectance, 5 percent for absorptivity, 5 percent average for dust, and 32 megawatts for combined convection and reradiation at the operating temperature of 515°C; Dm = effective mirror diameter; δ = angular standard deviation of the reflected light due to heliostat imperfections; Dr = receiver diameter.

in the summer there is sufficient daily energy to run at capacity all day and still charge the storage unit so that the evening market can also be supplied.

In an alternate mode of operation fossil fuels would be used when solar energy is not available, especially on cloudy days. Fossil fuels could also be used in the evening market, but some form of thermal storage is still required to ensure plant stability. Such a solar plant with fossil backup is classified as a fuel displacement plant and may be given little capacity credit. However, further depletion of our petroleum reserves may make such a facility acceptable. We have yet to develop an adequate methodology for estimating capacity credit for the solar component when fossil fuel is used in reserve.

A second form of storage is the use of suitable deep geological formations into which high-temperature fluids can be pumped. The requirement is a porous formation where leakage to the outside would be minimal, such as abandoned oil wells. Porous rock is a relatively good thermal insulator. If we consider a sufficiently large unit, the fractional loss per day is small because the surface-to-volume ratio becomes small. Calculation shows that geothermal storage for a 100-megawatt (electric) tower would require about 2 months to charge and then could be used cyclically each day to provide load-following capacity (*8*). Because the extraction is regenerative, injection and withdrawal temperatures could be very nearly equal and quite high. If, however, we should encounter difficulty in injecting or producing fluids at sufficiently high temperatures for power production, large quantities of process heat at 150°C and above are in demand and such geothermally stored heat can be harnessed to service those process needs.

Another approach to storage, which we believe deserves further emphasis, is chemical bond storage, with molecules having bond strengths of several electron volts per molecule. An obvious example is the electrolysis of water into hydrogen and oxygen. This method is under investigation for photovoltaic cells and wind energy systems but it is not the leading candidate if a thermal cycle is involved, because about 2/3 of the energy will be wasted in the thermodynamic cycle unless, perhaps, viable fuel cells are developed. The storage battery constitutes another form of chemical bond storage which is currently under intense study as electric storage for photovoltaic cells. Batteries provide more compact storage than hydrogen gas and are well suited for individual use, such as in an electric car.

Table 1. The 1977 cost estimates for a mass-produced 100-megawatt (electric) solar tower plant.

Subsystem	Relative cost (%)
Generator plant	30
Energy storage (6 hours)	11
Installed heliostat costs ($80 per square meter)	43
Receiver, tower, and piping	14
Spares, land, and yard	2
Total system: $1700 ± 15 percent	100

The Germans have under development a closed-cycle, decomposition-recombination chemical reaction in which methane and water react to form hydrogen and carbon monoxide [the process bears the acronym EVA-ADAM (*9*); the hydrogen-generating reactor is called EVA (Einzelsphaltrorvernsuchsanlage), and the back reactor is called ADAM as the mate to EVA]. This reaction is to be coupled to high-temperature, nuclear gas reactors to deliver heat at a substantial distance. Calculations indicate that more heat can be delivered by this system than through a thermodynamic-to-electric cycle, and transmission costs are less than for electricity. This cycle can possibly be developed for use with the solar tower, but techniques for banking the catalysts (removing the reactants while maintaining the catalyst bed at operating temperature) during sunless hours must be studied. Moreover, the gases involved require large-volume storage.

A most attractive form of chemical storage is the simulation of fossil fuels. One would like to use solar heat to decompose a liquid compound into several other liquids that can be stored or transported and recombined at will with the liberation of heat, Q. The liquid-liquid reaction would offer ease of handling and would allow storage of more energy in a given volume than either a chemical cycle involving gas reactants or a sensible heat storage system. The heat generated in the reaction can be used in home heating and cooling and, if it is of sufficient quality, in the production of electricity. If we consider the reaction between ammonia (NH_3), water, and sulfur trioxide (SO_3),

$$NH_3 + H_2O + SO_3 \rightarrow NH_4HSO_4 + Q \tag{1}$$

considerable heat is generated as the reaction processes exothermically to the right without a catalyst at temperatures up to 500°C (*10*). The chemicals are liquid at near room temperature and pressure (NH_3 requires some overpressure and SO_3 requires some heating to avoid solidification). The chemicals are cheap and abundant, and the density of energy storage is about 800 kilocalories per liter: about 1/7 that of gasoline or 10 to 20 times that of sensible heat stores.

Recycling of the chemicals would require the thermally activated decomposition of the ammonium hydrogen sulfate (NH_4HSO_4) into the compounds on the left in Eq. 1 and then separation. This back-reaction and separation have been carried out and at temperatures attainable with the solar tower (*10*). Basically, there is a temperature for each chemical system above which dissociation and absorption of energy occurs and below which the chemicals recombine with the release of energy. Such synthetic fuels can be readily integrated into our technological structure, displacing fossil fuels and bypassing the inefficient electrical generation cycle in many cases.

The development of methods for storage of sufficient energy to operate through several sunless days, or of a viable backup will probably be slow in coming, but, once such storage systems have been developed, solar plants in the Southwest can supply a significant amount of our national energy requirements by electrical transmission. The high-voltage direct-current net from the Northwest to the Southwest (1600 kilometers) is adequate demonstration that power can be economically transmitted over long distances. Therefore, it is possible to transmit power from Lubbock, Texas, in the sun-rich Southwest, to Detroit (1600 kilometers).

Environmental Concerns

For economic reasons, utilities have recommended the use of wet cooling systems in the pilot and demonstration plants. The dry cooling tower (Fig. 2) is somewhat more expensive and operates at a loss of a few points in plant efficiency, but dry cooling may be required to minimize environmental impact in the desert, a first-choice site for emplacement of the solar tower plants. With dry cooling towers, solar plants are expected to have a minimal environmental effect. In contrast to fossil-fired plants, the increase in global heat from a solar plant is a second-order effect since the system is simply converting incoming radiation to useful mechanical energy before it is ultimately deposited as heat by the electric utility. This figure compares favorably with conventional fossil-fired systems that deposit 3 to 4 units of thermal energy (waste heat) into the biosphere for each useful unit of energy utilized. In fact, continued dependence on nonsolar energy might eventually require the reflectance of sunlight back out into space to preserve the heat balance of the earth.

Economics

There are no technical barriers to the development of power with heliostats. The technology is available and plans are for a contract to be written with an engineering firm this year to initiate final design and construction of a first system, although it will be expensive. Cost estimates for the first-of-a-kind 10-megawatt (electric) pilot plant, scheduled to be completed in 1980, are in the range of $7,500 to $10,000 per kilowatt of installed electrical capacity, including provisions for thermal storage for 6 hours of operation beyond sunset (*11*). No dramatic technical discoveries are necessary to reduce this prototype cost by a factor of 5 to bring it into a range comparable to the $1000 per kilowatt (electric) currently required for the construction and fueling of nuclear plants.

A significant cost reduction will result from the better collector and turbine efficiency associated with an increase in plant size to 100 or 300 megawatts (electric). In addition, specific mass-production approaches have been identified which are likely to lead to the required cost reduction for an integrated large-scale, dedicated heliostat production facility. One such production facility would produce heliostats for ten 100-megawatt (electric) plants each year. If a facility sized to produce only one plant per year were built in 1985, a second in 1988, and an additional full-size production facility were built each year from 1990 to 2000, about 40 gigawatts (electric) of installed capacity could be on-line by the year 2000. This capacity is enough to meet the anticipated requirement for new intermediate electrical load for the entire Southwest and would require a land area of about 1400 square kilometers (550 square miles). Development of economic storage could expand this market manyfold.

Assuming at least 785 megawatts of capacity is constructed each year in an integrated and dedicated plant with a 30-year life, the midpoint cost of installed heliostats in 1975 dollars is $66 per square meter. Under the same assumptions, the total capital cost of a plant is given, in 1977 dollars, in Table 1. The $1700 per kilowatt (electric) includes 6 hours of thermal storage (*12*).

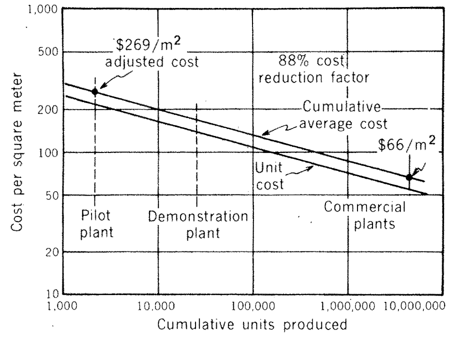

Fig. 5. Projected heliostat costs (1975 dollars). Mass-production learning would lower the average cost of $269 per square meter expected for the pilot plant heliostat to below $70 per square meter for commercial application after about 1 million units had been produced. This figure reflects projected cost reductions for a single facility resulting from integration of steel fabrication facilities, mirror and glass fabrication facilities, and experience-dictated improvements in plant operation, heliostat operation, and other factors. On the log-log scale, the upper line refers to the average value for all production to date, whereas the lower curve gives the cost projected for a single unit, which approaches $50 per square meter by the end of the production run of 25 to 30 years. (To convert to 1977 dollars multiply by 1.20.)

Once production of 100-megawatt (electric) units begins, costs would begin to drop as a result of learning curve effects. As an example, production of the first 10,000 Model T Fords resulted in an average cost, in constant 1958 dollars, of about $4000 for the cars produced in 1909. Continued cost improvement occurred in the manufacture of essentially the same car until 1927, at which time 14 million units had been produced. The cost for the last units of the production run was about $850 per unit (*13*). On the basis of this type of cost-reduction program, a reduction of 10 to 15 percent in the unit cost should be possible each time the total number of units produced is doubled until the bulk material costs predominate, and even then design refinements and new materials can further reduce costs. In Fig. 5 we show the anticipated learning curve for heliostats, where the upper curve represents the average cumulative cost for the entire production run and the lower curve is the unit production cost. Here $269 per square meter is the cost of the pilot plant and $66 per square meter is the average cost of heliostats produced by the plant after construction of approximately 20 gigawatts of capacity (1975 dollars).

Such a cost improvement permits us to put capital costs into perspective. A 10-megawatt (electric) pilot plant is estimated at $10,000 per kilowatt (electric) or less, whereas a first demonstration plant may cost $2500 per kilowatt (electric). To produce units selling in the range of $1700 per kilowatt (electric) requires that average heliostat costs, in 1977 dollars, be reduced to about $80 per square meter, which may require production of 5 million heliostats. In such a production run, the second million heliostats would already meet the cost requirements, having an average production cost of about $78 per square meter, whereas the first million would have an average cost of about $100 per square meter. Thus, the excess cost of the first million heliostats, each about 40 square meters in area and having an excess cost of $20 per square meter, is about $800 million. Compared to the expected cost of oil imports for 1977 of $40 billion, this is truly a small differential, which incidentally, will be paid back by even lower heliostat costs for the last 3 million heliostats produced in our hypothetical run of 5 million.

Since the cost of the heliostats is approximately half of the total cost of the commercial plant, less than $2 billion investment (subsidy) is required to stimulate a new technology that will integrate into the present utility structure. This amount should be compared to nuclear energy investments, recent space ventures, annual deficit of payments, 1976 oil import costs of $35 billion, and future escalation of oil costs.

There is sufficient unused desert land available in the United States to meet all of our energy needs by means of solar tower plants, an option not likely to be exercised. Energy production by solar towers would have an efficiency factor for land usage which would compare favorably with that of any renewable system presently under consideration. At a cost of $2000 per acre ($4900 per hectare), the land cost for a 100-megawatt (electric) plant is only $17 per kilowatt (electric).

Another indirect economic criterion is the energy amplification factor (EAF), defined as the useful energy produced over the useful life of a device divided by the capital energy required to create the device. Table 2 records an estimate of the energy required to produce materials, including transportation energy in manufacture and delivery, for the thermal component of a solar tower concentrator. Because this energy may have to be processed through a thermodynamic cycle with an efficiency of about 1/3, the collection time translates to less than 1 year. With the addition of the energy costs for fabrication, construction, and miscellaneous expenses, we expect the final required energy figure to be equivalent to less than 1.5 years, giving an EAF

Table 2. Material and transportation energy requirements for a 100-megawatt (electric) commercial solar tower system (fabrication and construction energy not included).

Part	Material (*12, 15*)	Weight (metric tons) (*12, 15*)	Energy required [megawatt-hours (thermal)]	Days to collect total energy	
				Thermal	Electric
28,605 heliostats (each 30.4 square meters)	Steel	23,084	144,055 (*18*)		
	Glass	13,959	45,196 (*16*)		
	Concrete	69,224	22,312 (*18*)		
	Sand	100,003	4,291		
	Polyurethane	257	715		
	Motors (copper)	372	8,152		
Receiver	Incoloy-800 and structural steel	1,127	7,655		
Riser and downcomer	Steel	182	1,135		
Tower	Concrete	41,757	13,517		
	Steel	1,266	7,899		
				70	210
Estimated transportation costs (*15*)			55,053	15	45
Total			309,980	85	255

of approximately 20 for a useful life of 30 years. This estimate can be compared to estimates for nuclear plants described in ERDA 76-1, where the EAF of a nuclear plant is estimated as 4 (*14*). Incidentally, the duty factor of the nuclear plant is taken realistically as 0.61, only 50 percent above the 0.41 expected for the solar plant with 6 hours of storage discussed here.

There still remains the energy cost of disposing of radioactive wastes and of shutting down a reactor after its useful life and safely disposing of the radioactive debris, whereas the steel used in heliostats can be reprocessed. The EAF factor clearly indicates a constraint which must be considered when deciding to build either nuclear or solar plants if the total fossil fuel requirements of the country are to be reduced over the next 25 years rather than expanded. The question of long-term economics requires the consideration not only of present dollars and capital development but also of long-term commitments to ensure both the availability of reliable sources of energy and the preservation of the environment.

The quantity of materials required in the solar tower design helps us to understand the economics of solar energy (Table 2). The heliostat cost of $66 per square meter appears reasonable if the cost of construction approximates $1 per pound or $2.25 per kilogram (for metal and glass). This represents an achievable goal, particularly if we realize that one can buy domestic pickup trucks in this country that sell for a little less than $1 per pound, and that a truck is a far more complex unit than a heliostat.

The cost of intermediate (load-following) power produced with the tower concept is estimated in the range of 80 mils per kilowatt-hour, based on a capital cost of $1700 per kilowatt (electric) and operating costs. We believe this cost is competitive. A charge of 30 percent was used for development of capital (the construction period is assumed to be 3 years), and the construction costs were amortized by means of a linearized fixed fee of 16 percent per year. Learning curve experience will lead to still lower capital costs for later production. The escalation of fuel costs will have no first-order effect upon constructed solar plants.

Conclusions

The estimated capital cost per kilowatt-hour of $1700 for solar tower plants is competitive with other means of energy production, such as hot-water nuclear reactors, including the complete fuel cycle. With 6 hours of thermal storage, the capacity factor is better than 0.41 compared to realistic capacity factors of 0.61 for nuclear reactors. Production costs seem reasonable, and there are no critical shortages of materials. Although there will obviously be improvements in design and management which will scale down costs, no radical technical discoveries are needed to construct and operate a solar energy plant. Once heliostats are in mass production, solar plant construction periods of only a few years are anticipated. The period for the construction of the pilot plant including final design is estimated at less than 3 years.

Most countries are in need of a long-range economic and political plan involving private enterprise and the federal government to develop a process for the national use of solar energy during the next hundred years. A national commitment would reduce the investment risk involved in building the first solar tower facilities. The greatest potential exists for adopting new technology in the utilities, but U.S. regulations essentially forbid the utilities to invest in new technology until it is proven over a period of time. Development of solar energy can reduce U.S. oil imports as well as help undeveloped countries that have no exports to offset the need for oil imports. A stable energy future demands that we examine all the energy options available.

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19. This work was supported in part by the University of Houston and NSF/RANN grant SE/GI-39456, ERDA grants AER73-07950 A03 and EG-76-G-05-5178, and ERDA contract E(04-3)-1108 with G. Kaplan as program manager. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of either ERDA or NSF.