SOLAR ENERGY—PROSPECTUS 1978

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ABSTRACT

By way of introduction, the availability of solor energy is discussed by considering such ideas as solar constant, sun angles, solar spectrum, and direct and diffuse components of radiation. Solar thermal conversion is discussed via consideration of flat plate and concentrating solar collectors, including geometries and test standards. Solar energy applications are reviewed giving current status and estimated future importance of the following: heating, cooling and hot water, thermal-electric power genertion, photo voltaic power generation, thermal mechanical pumping, and process heat supply.

INTRODUCTION

Solar energy has received a great deal of attention in recent years as a possible alternative energy resource with potential for reducing the nation's dependence on energy from fossil and nuclear fuels. Advocates point out that solar energy is widely available, non-depletable, not controllable by cartels, non-polluting, etc. Detractors point out solar energy's low intensity at the earth's surface and such other disadvantages as its daily intermittency, seasonal variability, and dependence on the weather. There is a great deal of activity in government-sponsored research and commercial development directed toward the use of solar energy to solve some of the energy-related problems of our country.

In this paper as assessment of solar energy technology will be made, not from an advocacy position, but from a position of wanting to provide a current, informative picture of the status of solar energy in the United States.

FUNDAMENTALS

There is a number which indicates the magnitude of available solar energy; it is called the "solar constant." The solar constant is technically defined as the intensity of the sun's radiation on a surface normal to the rays in space at a distance of one Astronomical Unit (92,955,888 miles average earth-sun distance). The solar constant has a value of 1.94 cal/(cm^2-min) or 429.2 Btuh/ft^2 or 135.3 mW/cm^2. Another set of units in common use is Langleys/min, which is equivalent to cal/(cm^2-min).

Unless one is concerned with the solar power satellite, however, the solar constant is not the appropriate measure of available solar energy. For earth-bound projects the term "solar insolation" stands for the radiant energy available at a particular site. This amount of energy is variable due to the relative motion of the earth and sun and due to atmospheric (water vapor and dust) conditions over the site. Diurnal (daily) and seasonal variations due to the earth's rotation about a tilted axis and revolution around the sun can be accounted for by consideration of the sun angles. The earth's axis tilt (23° 27 min to the plane of the earth's orbit and the sun's equator) results in a daily variation in the angle between the earth-sun line and the earth's equator, the declination angle. The declination angle varies from zero (spring and fall equinox) to 23° 27 min (winter and summer solstices). This variation causes varying hours of daylight and darkness and summer-winter differences in the variation of solar radiation at a given location. The sun's position relative to a given location (longitude and latitude) is defined in a local horizon plane by altitude and azimuth angles: altitude being the angle above the horizon (zero at sunrise and sunset) and azimuth being the angle between due south direction and the projection of the earth-sun line on the horizontal.

Another important sun angle is the inclination angle, the angle the sun's rays form with a normal line to the surface of interest. This angle determines the intensity of the direct radiation striking the surface. For more complete discussion of these sun angles and tabulations of their effects, see the literature.[1,2]

Solar energy comes from the sun in the form of electro-magnetic radiation equivalent to that from a black body at a temperature of 5,762° K (10,372° R). Its spectral content is important to consider in order to effectively receive that energy and convert it to useable form. The wave lengths range from X-ray (0.1μ) to radio waves (100m) but 99% of the energy is between 0.28μ and 4.96μ. About 9% is ultraviolet ($<0.4\mu$); another 38% is in the visible range (0.4μ to 0.7μ) and the infrared region contains about 53%.

The earth's atmosphere scatters part of the sun's direct radiation, causing the sky to appear blue in color on clear days. Part of this scattered radiation ultimately reaches the earth's surface as the diffuse component of the sun's radiation. On cloudy or hazy days only this diffuse component reaches the earth's surface. Calculation methods exist for estimating this diffuse component,[1,2] but local measurements of both direct and total radiation will best allow its determination.

The maximum daily amount of solar energy which can be received at a given location is that which falls on a flat plate with its surface normal to the sun's rays so that it receives both direct and diffuse radiation. For fixed collectors the maximum annual energy received will be obtained if they are tilted from the horizontal by an angle equal to the latitude and are faced due south (northern hemisphere). To favor wintertime applications (heating) the tilt angle should be increased above latitude value (up to 15°); to favor summertime applications (cooling) the tilt angle should be decreased from latitude value (by up to 15°).

Incoming solar energy must be converted to useable form—chemical, electrical or thermal. Conversion to chemical energy is most familiar in natural photosynthesis; man-made applications of this type are not yet important as energy sources. Solar-thermal and solar-electric conversions are receiving a great deal of attention and will be the remaining focus of this paper.

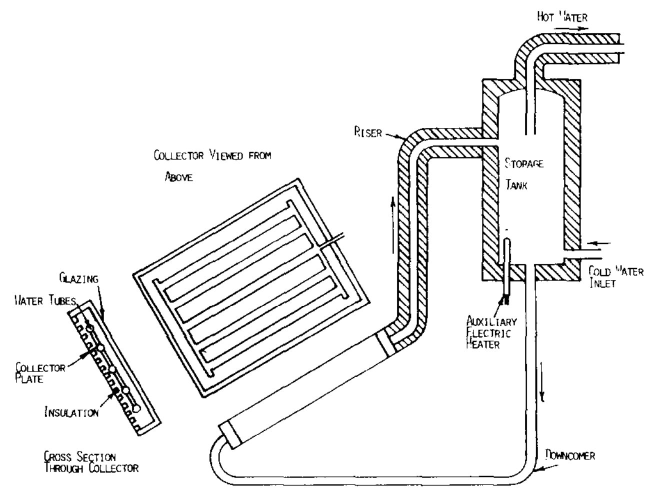

FIGURE 1—THERMOSYPHON WATER HEATER

Solar thermal conversion is most often accomplished by the familiar flat plate collector. One common configuration is shown in Figure No. 1, an illustration of a thermosyphon water heater. The essential features of all flat plate collectors are included: glazing, collector plate, tubing, insulation, frame. The glazing (or covering) usually consists of one, two, or three covers of a transparent material, glass or plastic. The purpose of the glazing is to reduce heat losses due to re-radiation and also due to convection. A glazing capable of transmitting at least 90% of incoming short wavelength radiation while allowing a very low amount of the long wavelength radiation emitted by the collector plate to be transmitted outward is desired. The primary function of the collector is performed by the collector (or absorber) plate, that is, conversion to thermal or heat energy. The collector plate (aluminum, copper, or steel) absorbs the incoming radiation and conducts the heat to a circulating fluid (air, water, or other). Commonly, the surface is blackened (e.g. with flat black paint) to assist the absorption and reduce reflectance and emittance. Use of "selective coatings" which have very high absorption for short wavelength radiation (incoming) and very low emittance for long wavelength can significantly increase the performance of a collector.

Tubes are necessary for heating liquids; if air is to be heated, the channel between the collector plate (which may be finned) and the glazing can serve as a conduit. Tubes may be either integral with the collector plate or else must be attached with good thermal contact with the collector plate. Insulation to reduce heat losses and the frame or case complete the essentials for flat plate solar collectors. There are many variations of this basic idea, almost as many as there are fertile minds applied to the product.

Collector performance is best specified in terms of efficiency, which is in turn defined as useful energy collected divided by solar radiation available. For flat plate collectors standard methods of determining collector efficiencies for comparative purposes are specified by ASHRAE 93-77.[3] Tests are generally performed outdoors on clear days near solar noon under steady conditions. Test results are usually presented in a plot of instantaneous efficiency versus an insolation factor: inlet temperature minus ambient temperature divided by measured radiation on the collector surface per unit area. Test data usually can be represented by a straight line. These standard tests are meant to give a basis for comparison of collector performance. One cannot merely obtain the most efficient one available; the choice of a collector for a particular application depends on comparing costs and performance of a system, including the performance of a collector at a given location.

Much higher temperatures can be obtained if the sun's rays are concentrated from a larger collector area to a relatively smaller absorption area. These higher temperatures have the potential to generate steam or other vapor for powering electro-mechanical conversion machinery or to power refrigeration cooling equipment. Such concentrators can take the form of parabolic troughs, parabolic dish reflectors, or fresnel lenses (linear or two dimensional). The disadvantages of these types of collectors are that they must depend on the direct rays of the sun (will not work at all if it's hazy or cloudy) and that they must be continuously pointed (tracking) at the sun. The higher costs and mechanical complexity due to the tracking requirement has so far limited applications to special cases where flat plate collectors are not feasible. There are several systems utilizing these types of collectors in operation. There are as yet no accepted performance or test standards for concentrating collectors although efficiency curves similar to those for flat plate collectors are in use.

APPLICATIONS

The first part of this paper has recounted some of the fundamentals of solar energy which concern applications for our energy needs. The second part will discuss these applications and assess their current status. The simplest application that may be considered is providing heated water for domestic use. This application has a considerable history with hundreds of units being used in Arizona, California, and Florida in the early 1900's, and mass production numbers in current use in the Middle East, Japan, and Australia. Figure No. 1 shows a thermosyphon unit of the simplest type. Water heated in the collector tubes rises to the upper part of the storage tank forcing cooler water out the bottom of the tank and into the collector. The process continues so long as the sun shines on the collector. Water temperatures of 120° to 165° F can be regularly obtained with 16 to 20 sq ft of collector area with a 40 to 60 gal tank.

A somewhat more complicated water heater is shown in Figure No. 2. In this system the mechanical circulation of the water is provided, and an intermediate storage tank holds heated water which is in turn fed to a conventional hot-water heater. With prices for such systems ranging from $1,000 to $4,000, it's fair to ask if they are currently economical. For private homes only large families that had been using electricity to heat water may expect to recover their costs in a reasonable amount

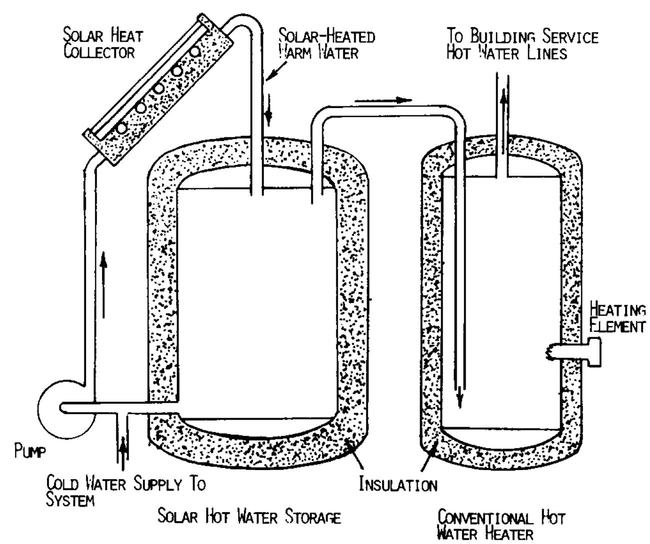

FIGURE 2—SOLAR HOT WATER HEATER

of time (say less than 5 years). It must be re-emphasized that such comments are intended only to give a perspective; actual savings are very much dependent on the particular implementation including current, local costs. By the way, it's fair to say that solar water heating systems can make more sense economically for larger capacity systems such as would be used for multifamily dwellings, dormitories, motel/hotels, etc.

A recent experiment with solar hot-water heaters run by the New England Electric Company points out some of the problems that may be expected as solar applications proliferate. The electric company subsidized the installation of 100 solar hot-water heating systems in private homes. The units were purchased on the open market and were of a variety of designs. Mostly they were installed by authorized dealers. Predictions were that savings would be approximately 50%. After a year's operation the average savings were only about 17% with several units having less than 5% savings. Costs ranged from about $1,500 to $3,000 per unit. Detailed investigation of the reasons for the poor showing reveals that many mistakes, some very obvious ones, were made regarding the installations. As these mistakes were corrected, savings approached the predictions. This points up the fact that product support activities, including the education and training of the installers and distributors, must be developed.

The next easiest kind of solar application is space heating for residences as illustrated in Figure No. 3. Solar-heated water from a storage tank is circulated to a water-air heat exchanger in a room heater unit or in the duct of a central forced-air system. The storage can economically provide 2 to 3 days' storage for cloudy periods. Beyond that, some conventional back-up heating system is required. Similar systems are available using air as the circulating medium and rock or phase-change storage systems. Such a heating system, sized to supply about 80% of the heating and hot water requirements for an average sized house, might cost $6,000 to $8,000.

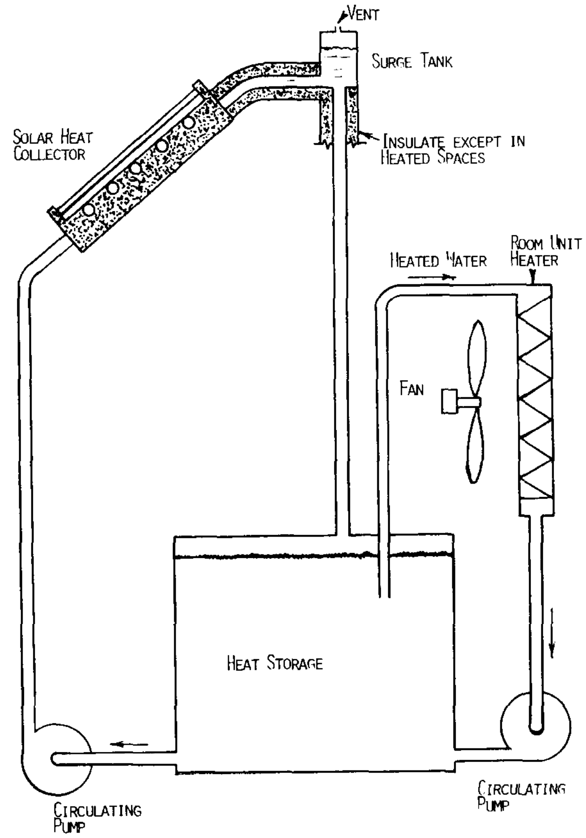

FIGURE 3 SOLAR SPACE HEATING SYSTEM

The addition of a heat pump to such a solar heating system, as illustrated in Figure No. 4, provides a well suited back-up heating system and the provision for cooling as well. This system appears particularly well suited for the Southwest region of the U.S. The heat pump will be more efficient as a heater when operating out of a depleted thermal storage tank as opposed to the lower outside temperatures. It is possible that the diffuse radiation which can be used by flat plate collectors will provide enough heat input during cloudy weather to obviate the need for extensive resistance heating, which is much less efficient. The existence of a storage facility allows the possibility of storing chilled water during the cooling season so that nighttime operation of the heat pump can be realized. Because of lower outside temperatures at night, there is a savings in terms of increased efficiency. It may also be that nighttime electric energy can be obtained at reduced rates, which would further increase savings. The addition of the heat pump would increase the system costs to approximately $11,000 for an average sized home. If conventional energy costs the equivalent of 5¢ to 6¢ per kilowatt-hour for electricity, then such a system might be expected to recover its cost in less than 10 years.

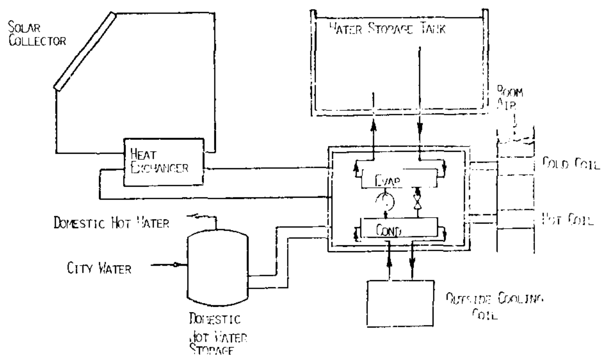

FIGURE 4 SOLAR ASSISTED HEAT PUMP

Solar cooling is presently accomplished only with the use of absorption cycle refrigeration equipment. The equipment which is presently available in residential sized units (3 tons) is derived from gas fired air-conditioners which have been used in the Southwest for years. The gas flame burner has been replaced with a water-coil heater for use with solar-heated water. Such a system including heating and hot-water provisions could be expected to cost about $15,000 and to supply only about 40% of the cooling for an average size home. This kind of system is not considered economical at the present time.

An active demonstration program for the above applications has been pursued by the Departments of Energy (DOE) and of Housing and Urban Development (HUD). These programs have been aimed toward subsidizing a developing commercial capability and toward obtaining experience in operating such systems to determine what savings can be accomplished. This demonstration phase is nearing an end, after which time the private segment will be left to determine the viability of continuing with such installations. Incentives, mostly in the form of tax relief for producers and purchasers, are expected to continue as more states and the federal government adopt them. Examples of such incentives are those included in the energy bill which is now in Congress and those recently signed into law in California. The federal incentives are expected to offer tax credits on the order of 40% of the first $1,000 and 25% of the next $6,000 spent on solar heating devices for a specified period of time (e.g., through 1984). In California, where 150,000 citizens are expected to install solar devices in the next 3 years, incentives are more generous. A tax credit of up to 55% up to a maximum of $3,000 against state income tax is allowed. Commercial or industrial concerns will qualify for 25% credit against state income tax for systems costing more than $6,000. Consumer protection in the form of regulations for testing, inspection, certification, and installation is in the planning stage. Other states now offering tax credits include Arkansas, Montana, North Carolina, and Oklahoma.

The solar-thermal conversion applications discussed above are currently the most widespread and are further along in development than others because of their relative simplicity. Some more difficult solar applications will now be discussed, including thermal-electric power generation, photo-voltaic power generation, and thermal-mechanical pumping applications. These applications require a higher level of technology and large amounts of capital funds for development, and so practical implementations will be delayed until the 1980's and beyond.

There are two different concepts for central thermal-electric power generation under consideration. One concept is the "power-tower." A field of reflector mirrors will concentrate the sun's rays on a steam generator mounted on a tower in the midst of the field. Steam will run a conventional generating plant. A prototype has been constructed and is currently being tested by the Sandia Labs in New Mexico. A 10-megawatt plant is being designed by the Southern California Edison Company and the Los Angeles Department of Water and Power for a location in the Mojave Desert. A different approach is being taken in the design of a Fixed Mirror Distributed Focus Solar Thermal Electric Plant at Crosbyton, Texas. The plant will consist of several 60 to 90 ft diameter fixed, spherically shaped mirrors which focus the sun's rays on a linear receiver.The receiver will carry a steam generator (1,000°F and 900 psi) which will power a turbo-generator system. The receiver must track the focus in two dimensions as the sun moves across the sky.

Photo-voltaic power generation is a product of the U.S. space program. Now the rush is on to reduce the costs to a level where terrestrial applications are feasible. Costs have already been reduced from several hundred dollars per peak watt of power a few years ago to about $21 in 1976, $15 in 1977, and $11 in recently signed contracts for 1978 delivery. Such costs are feasible only for remote, relatively small-scale applications such as remote weather stations and navigation bouys. However, cost reductions hold out the hope for more extensive applications of a more practical sort. The DOE is already planning large-scale experiments to obtain operating experience and to identify problem areas.

An irrigation project is in operation in Nebraska utilizing 100,000 silicon cells to generate 25 kilowatts of peak power. The arrays power a 10-hp power pump 12 hours a day to irrigate 80 acres of corn. Water is pumped at the rate of 1,000 gal/min. During the irrigation off-season the power is used to run two 27-ft diameter drying bins each of which holds 6,000 bushels of corn. DOE predicts that such irrigation projects will be economically feasible in the Southwest by 1983 and by 1986 for the Midwest. Such systems are expected to be available for between $30,000 and $40,000 by the mid-1980's.

Similar experimental irrigation projects are operating in Arizona and New Mexico using solar thermal-mechanical pumping units. Parabolic trough reflecting, concentrating collectors are heating a refrigerant-type working fluid to power a Rankine cycle heat engine which in turn powers the irrigation pumps. The Gila River project near Phoenix, Arizona, is a 50-hp pumping unit capable of delivering 10,000 gal/min of irrigation water through a 14-ft lift from a recovery basin. The New Mexico system, rated at 25 hp, lifts 630 gal/min from a 110-ft deep well. Once again the limiting factor on these kinds of projects is the very high development costs which are estimated at $3,000 to $5,000 per hp including engines and collectors in production quantities.

If these projects seem far away, we might close by considering the Satellite Solar Power Station (SSPS) concept which is being studied. A series of satellites each with large (12-sq-mi area) solar-collector arrays would be placed in synchronous orbit about the earth. Microwave energy would be beamed to a 20-sq-mi receiving antenna on the earth. A 5-gigawatt SSPS would cost about $8 billion or about $1.5/watt. The socio-economic-legal implications on both national and international levels are as vast as the technology. However, this is, at least for now, the upper limit to the kinds of solar energy applications being considered.

REFERENCES

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