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THE APPLICATION OF SOLAR THERMAL
ENERGY TO BUILDINGS AND INDUSTRY

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THE APPLICATION OF SOLAR THERMAL ENERGY TO BUILDINGS AND INDUSTRY

Charles F. Kutscher*

I. BUILDINGS

Although the use of solar energy for space heating was common in ancient civilizations (e.g., south facing orientations of cliff dwellings, Roman camps) cheap energy rendered it a lost art in the United States. Even today most homes with large areas of glass are built to face a view or street, and that direction is usually not toward the sun. As prices of previously cheap fossil fuels began rising in the early 1970's, the sun once again became an obvious alternative source of energy.

The sun is often referred to as a source of free energy. This is really only true for applications such as sunbathing which require no equipment. When we want to use the radiant energy of the sun to heat the air in our houses or wash water we usually have to do three things: capture its heat, store it (because it is an intermittent source), and distribute it. All three of these cost money, but the first is typically the biggest expense.

For space heating purposes, the cheapest way to capture the sun's rays is to allow the sun to directly enter the living space or strike a wall in communication with the living space. Figure 1 shows the direct gain concept. In the winter the sun is low in the sky and directly enters through the south glass. In the summer the sun is high and the sharper angle cuts down on the amount of sunlight entering. A horizontal overhang further reduces the risk of summer overheating. To keep the house warm at night (and to prevent overheating during the day) the house should have a large thermal mass within the insulation to serve as storage and to moderate temperature fluctuations.

The use of thermal mass is clearly illustrated by the Trombe wall concept of Fig. 2. Developed by Felix Trombe in Odeillo, France, in the 1950s it consists of a simple masonry wall with an outer covering of glass and an air gap in between. Sun striking the wall heats the air in the gap which rises and enters the house by natural convection. By night time, the wall has heated sufficiently to supply heat to the room by radiation and convection from the inside surface.

Another concept is the use of a "sunspace" or south-facing greenhouse shown in Fig. 3. Such a space will heat up from the sun, and this heat can be transferred into the house by natural convection. Like the others just mentioned, this idea is an example of passive solar energy, defined as a solar energy system which uses natural means for heat transport. Trombe walls and attached sunspaces often work best when aided by a fan and today even passive solar purists are at least tolerating such technological contributions.

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Figure 1. A Direct-Gain Heating System.

An alternative for heating a building and domestic hot water is the so-called active solar energy system which will be the main topic of this paper. An active system uses pumps and fans to circulate heat and employs the solar collectors we have all seen on rooftops. Solar collectors are nothing more than heat exchangers which transfer the radiant energy of sunlight into the sensible heat of a working fluid.

Flat-Plate Collectors

There are many different types of collectors, each corresponding to a different temperature range. The most common type is the flat-plate collector. It consists of the following basic components:

- Absorber plate—usually copper, steel, aluminum, or plastic; surface covered with flat black paint or a special selective coating to maximize absorption and minimize reradiation.

Figure 2. Storage Wall in the Heating Mode.

Figure 3. Attached Sunspace Heating System.

- Flow passages—in the case of liquids, flow is usually through tubes attached to, or an integral part of, the absorber plate. In the case of air, flow occurs above and/or below the plate, and heat-transfer surface area is maximized by means of fins, slots, or metal screening.
- Cover plate(s)—one, two, or three transparent covers are used to reduce convective and radiative heat losses to the outside air. Glass and various plastic materials are commonly used.
- Insulation—used to reduce heat losses out the back and sides of the collector, typically fiberglass or polyurethane.
- Enclosure—a box to hold collector components together and protect them from the weather.

Examples of various flat-plate collector configurations are shown in Fig. 4.

A great deal of effort has been devoted to improving the performance of flat-plate collectors. These improvements either increase the optical efficiency of the collector or decrease the thermal losses. Treatment of a glass cover to reduce reflection can increase performance by as much as 4% [1]. Coatings on the inner glass surface to reflect the longwave radiation (which would otherwise heat the glass) have been used, though these also reduce the transmittance. A honeycomb located between the inner cover and absorber plate can reduce both convective and radiative heat losses [2]. Planar reflectors used in front of a row of flat-plate collectors can increase energy collection by as much as 40% over a heating season [3]. Most of these techniques, while offering varying advantages, have not been widely applied.

Advanced Collector Designs

As the temperature requirement increases, the efficiency of a flat-plate collector rapidly falls off. Other collector alternatives are often chosen, particularly for supplying 195°F (91°C) water to operate an absorption chiller. Examples of some of the more commonly used advanced collector designs are discussed below.

Evacuated Tube

One way to reduce convective heat losses is to use a vacuum between the glazing and absorber surface. Since such a vacuum would cause a typical flat-plate collector to collapse, this technique is used in conjunction with a tubular design. There are various types of evacuated tube collectors on the market.

One design, shown in Fig. 5, uses three concentric glass tubes. Fluid flows into the annular space between the inner and second tubes and back out the inner tube. The annulus between the second and third (outer) tube is evacuated, and the outside of the second tube contains a selective coating.

Another design (Fig. 6) employs only two concentric glass tubes with the space between evacuated and the outer surface of the inner tube containing the absorptive coating. A metal fin conforms to the inside surface of the inner tube, and to this attached a copper U-tube which carries the fluid. The U-tube readily accommodates thermal expansion, and glass breakage will not result in a leak.

Figure 4. Common Flat-Plate Collector Configurations.

Figure 5. Concentric Glass Evacuated-Tube Collector.

Figure 6. Evacuated-Tube Collector with Copper Flow Tube.

Various shapes of reflectors are usually used behind evacuated tubes and provide a small amount of concentration. Evacuated tubes can collect both direct and diffuse solar radiation and do not require tracking. Because of the extremely high stagnation temperatures [over 600°F (316°C)] that evacuated tube collectors can reach, thermal shocking with cold water has sometimes been a problem.

Parabolic Troughs

Another way to cut down on heat losses that reduce efficiency is to concentrate the solar energy onto a smaller absorber surface. The most commonly used concentrator is a parabolic reflector trough with an absorber pipe located along the focal line as shown in Fig. 7. The collectors can be oriented east-west or north-south. In most cases, concentration ratios (ratio of aperture to absorber area) are high enough that continuous tracking is required even in the case of east-west troughs. Since most diffuse radiation is outside the concentrator's "acceptance angle," only direct radiation can be collected. As a result, a concentrating col-

lector cannot utilize as much of the available sunlight as a flat-plate collector. The differential between direct and direct diffuse radiation is small, and, in some cloudy climates, this disadvantage may more than offset the gain in efficiency.

Fresnel Lens

Rather than reflecting the sunlight onto an absorber pipe, one can instead refract it as shown in Fig. 8. Although this can be done with a convex lens, a Fresnel lens (consisting of many small refractive surfaces) is ordinarily employed since it is cheaper, lighter, and absorbs less radiant energy. For low-concentration applications, the Fresnel lens design has roughly the same advantages and drawbacks as the trough collectors.

Figure 7. Parabolic-Trough Collector.

Figure 8. Concentration with a Fresnel Lens.

Compound Parabolic Concentrator (CPC)

This design, as shown in Fig. 9, consists of a trough comprised of two half-parabolic reflectors with an absorber surface located at the bottom of the trough. Developed by Roland Winston of Argonne National Laboratory, this design

Figure 9. A CPC Collector Module.

has the advantage of providing a wide acceptance angle at low concentration ratios. The CPC is a nonimaging concentrator and essentially "funnels" the radiation rather than focusing it. If oriented east-west, troughs with a low concentration ratio would require only seasonal adjustment and would collect a considerable amount of diffuse as well as direct radiation. Unlike the other concentrators, its reflective surface need not be a highly specular and can thus better tolerate dust and degradation. A disadvantage is the relatively large amount of reflector area required. The CPC collector is still in the development phase.

Which collector is best for a given application is a function of the temperature required and cost. Basically one strives to choose that collector for which the ratio of installed cost per unit of energy delivered is lowest.

Domestic Hot Water

Since the efficiency of a collector is highest for low-temperature applications the heating of domestic hot water (DHW) is usually the first consideration for a typical household. (For homes with swimming pools, of course, solar energy can be an attractive means of extending the swimming season, also.) A number of different types of DHW systems have been used. The collector loop can be "open" with city water supplied directly through the collectors and ultimately to the hot water taps. Or a closed system can be used in which the collector fluid (usually antifreeze-water mixture) is recirculated through the collectors and a heat exchanger is used to transfer heat to the domestic water side. This eliminates the need for draindown of the collectors in freezing climates, but the heat exchanger exacts a performance penalty.

Solar hot water systems can also be of the one- or two-tank variety. Systems using electric power backup will often have a single tank as shown in Fig. 10. Here one tank serves both as the solar storage tank and the auxiliary fired tank. Typically, the electric heating element will be located near the top of the tank and supply water will be drawn from the top (hottest) part of the tank. The bottom of the tank will remain cooler to supply the lowest temperature water to the collectors thus maximizing collector efficiency.

Heating just the top of the tank is not practical with a gas-fired tank, so gas systems usually employ an extra solar or preheat tank (see Fig. 11). The preheated water in the solar tank is drawn through the fired tank where it is boosted up to the required temperature. Two-tank systems have the advantage of supplying the lowest possible temperature to the collector array, since the auxiliary energy is never added to the solar tank. However, they have more heat losses, due to the extra surface area of two tanks, and, of course, two tanks cost more than one. Also, in a typical two-tank system solar energy cannot be utilized to make up standby losses from the fired tank during times when hot water is not being used.

Although a pump is typically used in solar hot water systems, passive systems which rely on natural convection have worked successfully. In a so-called thermosiphon hot water system the storage tank is located above the collector. The water in the collectors is heated by the sun and rises to the storage tank. While such systems have generally been limited to nonfreezing climates several systems employing freon as the working fluid have worked well in freezing weather.

Figure 10. Closed-Loop Single-Tank Solar Domestic Hot Water System Using Electric Auxiliary.
SOURCE: Ref. 5.

Figure 11. Closed-Loop Double-Tank Solar Domestic Hot Water System Using Electric Auxiliary.
SOURCE: Ref. 5.

Maximum performance of a solar DHW system can be achieved by minimizing the hot water temperature supplied to the faucets. For most home uses, a 120°F set-point temperature is sufficient. Only a dishwasher requires higher temperatures (for dissolving animal fat) and these can be achieved by using an instantaneous electric hot water heater at the point of need. (One dishwasher on the market now contains one.) In many building applications, hot water is used mainly for lavatory sinks. As a result, some buildings now have only one faucet for warm water. This saves energy as compared to the situation of mixing hot water with cold to achieve the desired wash temperature.

Space Heating

Most homes in the United States are heated with radiators, baseboard convectors, or forced hot air. To work efficiently, the first two require higher temperatures than the typical solar collector system can supply. Temperatures of a forced hot air system, on the other hand, can be lowered by a compensating increase in air flow rate. Thus while a conventional system might use air at 140°F, a solar system could supply 120°F air at a higher flowrate, thereby delivering the same amount of heat.

For solar heating applications either a liquid or air solar collector system can be used. In a liquid system, hot water from a solar storage tank is circulated through a fan-coil unit where it heats the room air supply as shown in Fig. 12. This liquid collector system lends itself readily to the additional heating of domestic hot water. This serves to better utilize the collector array which would otherwise sit idle during the summer months.

Figure 12. Typical Combined Space and Domestic Hot Water System Configuration.

Air collectors can also be used for space heating with hot air being supplied directly from the collectors to the building air registers or to a rock and storage bin as shown in Fig. 13. At night warm air is extracted from the rock storage bin to heat the house. An air collector system can also be used to heat domestic hot water by use of an air-to-water heat exchanger, but this is not as efficient as in a liquid system.

Air systems have the advantage of no freezing, boiling, corrosion, or liquid leakage problems. However, ducts take up more space than pipes, about three times the storage volume is needed, and fan power requirements can be considerably higher than those for pumping power.

Whether a liquid or air heating system is used, the typical control strategy is to use a two-stage thermostat. When the building temperature falls below an upper set-point temperature, solar heating is initiated. If solar energy is adequate, it will eventually satisfy the thermostat setting requirement and shut off. If it is inadequate, the room temperature will eventually drop to a lower set point and auxiliary heating will be initiated.

In addition to applications in which solar energy heats a building directly, it can also be used indirectly in combination with a heat pump. In a so-called series arrangement solar collectors heat up a storage tank which is then used as the heat

Figure 13. Example of an Air Collector Solar Heated Domestic Hot Water System.

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source for the heat pump which boosts the temperature to a heat sink (see Fig. 14). The heat pump allows inexpensive collectors to be used since sink temperatures less than 90°F are useful. And the collectors allow the heat pump to operate at a high coefficient of performance.

Figure 14. Example of a Solar-Assisted Heat Pump System.
SOURCE: Ref. 2.

Solar Cooling

People are often surprised to learn that solar thermal energy can be used to cool a building. There are three basic ways which have received considerable attention:

Absorption - The absorption chiller is thermodynamically similar to a heat pump (or air conditioner) except that heat energy is input in place of the mechanical energy of a compressor and chemical absorption does the job of compressing the refrigerant. Typically lithium bromide is used as an absorbent and water serves as the refrigerant. This principle is the same one that was used in old gas refrigerators. A basic solar cooling system using an absorption chiller is shown in Fig. 15.

Rankine - In this application the power cycle used in electric generating plants is used to run not a turbine but the compressor of a heat pump. So rather than using electricity to run an air conditioner you are essentially using solar energy to run a small power plant at home. The combination power/refrigerant cycles are shown in Fig. 16. Whereas power plants use fossil or nuclear fuels to produce steam and pressurized water at high temperatures, Rankine engines using solar energy must run at lower temperatures and thus often employ Freon as the working Rankine cycle fluid.

Figure 15. Typical Solar Absorption-Cooling System.

Figure 16. Combined Heat Engine/Mechanical Refrigerator System.

SOURCE: Solar Energy for Heating and Cooling--Commercial and Residential. Summer Conference Proceedings. 1977 (July). Ann Arbor, MI: University of Michigan.

Adsorption - Just as the absorption chiller utilizes chemical absorption in a refrigerant cycle, chemical adsorption (attraction of a desiccant surface for water molecules) can be used. The most common desiccant system is somewhat different in that it uses an open-cycle system in which air is first dried by passage through a desiccant bed and then cooled with an evaporative (or "swamp") cooler. Solar heated air is used to dry (i.e., regenerate) the desiccant. Evaporative coolers which cool air through the evaporation of water don't work well in humid climates where the air already contains a large amount of water. Desiccant systems allow evaporative coolers to be used in such a climate (see Fig. 17).

Figure 17. A Desiccant Cooling System Operating in the Vent Cycle.

System Design and Sizing

A variety of design aids and handbooks are available for designing solar energy systems for buildings. For residential applications, two volumes published by Colorado State University [4] describe system design, sizing, operation and installation. For domestic hot water systems a HUD* publication entitled Installation Guidelines for Solar DHW Systems [5] is also very useful. The most popular collector sizing computer program is F-CHART, available from the University of Wisconsin.

For both passive and active commercial building applications, Solar Design Workbook [6], published by the Solar Energy Research Institute for the Solar Federal Buildings Program, is a comprehensive document. Nominal design parameters for typical air and liquid heating systems developed by Los Alamos Scientific Laboratory are discussed in that volume (see Table 1).

To properly size a system a complete economic analysis is needed. The basic approach is to calculate the present cost of the solar system including initial investment and present value of system maintenance over its life as well as the present worth of fuel savings over the system life. The difference between these is then plotted as a function of collector area and the collector area yielding maximum savings is chosen (see Fig. 18). A computer service using a program called SOLCOST is now available to perform life-cycle analysis of solar heating and cooling (SHAC) systems.

* Department of Housing and Urban Development.

Table 1. THE STANDARD LIQUID SYSTEM.

Values of parameters used for the "standard" solar heating system that includes liquid-heating solar collectors, a heat exchanger, and water tank thermal storage. The values are normalized to 1 sq ft of collector (sq ft_c).

Parameter	Nominal Value
Solar Collector	
1. Orientation	Due south
2. Tilt (from horizontal)	Lat +10°
3. Number of glazings	1
4. Glass transmissivity (at normal incidence)	0.86 (6% absorption* 8% reflections)
5. Surface absorptance (solar)	0.98
6. Surface emittance (IR)	0.89
7. Coolant flow rate (mC _p /sq ft _c)	0.04 gpm water/sq ft _c (20 Btu/hr-F-sq ft _c)
8. Heat transfer coefficient to coolant (UA/sq ft _c)	30 Btu/hr-F-sq ft _c
9. Back insulation U-value (UA/sq ft _c)	0.083 Btu/hr-F-sq ft _c
10. Coolant heat capacity rate (mC _p /sq ft _c)	1 Btu/hr-F-sq ft _c
Collector Piping	
11. Heat loss coefficient, to ambient (UA/sq ft _c)	0.04 Btu/hr-F-sq ft _c (U = 0.3 Btu/hr-F = sq ft _{pipe} or 1 in. insulation of k = 0.025 Btu/hr-ft-F)
Heat Exchanger	
12. Heat transfer coefficient (UA/sq ft _c)	10 Btu/hr-F-sq ft _c
Thermal Storage	
13. Heat capacity	1.6 gal water/sq ft _c (15 Btu/F-sq ft _c)
14. Heat loss coefficient (UA/sq ft _c), assuming all heat loss is to heated space	0 Btu/hr-F-sq ft _c
Controls	
Building maintained at 70 F	
Collectors on when advantageous	

*These values apply for normal incidence on ordinary double-strength glass (1/8 in.). For other angles of incidence, the Fresnel equation is used.

Figure 18. Determining Optimum Collector Area from Life-Cycle Costs (LCC) and Total Life-Cycle Cost (TLCC) of Solar and Auxiliary Heating

The typical cost breakdowns for solar heating and cooling projects funded by the government are given in Table 2. It can be seen here that collectors are still a major cost element. Because of the large "up front" costs of a solar energy system, payback periods can be long, thus discouraging homeowners from purchasing solar energy systems. Federal and state tax incentives have certainly helped. Also new financing arrangements have given solar a boost. For example, if a solar hot water system is included on a new house, the cost of the system can be absorbed into the home mortgage resulting in a relatively small increase in monthly payments to the home purchaser.

The number of primary concern in adopting solar is the life-cycle cost per unit of energy delivered, or \$/MBtu. While the cost has been a major hurdle for solar energy, the performance has also not come as easily as some people originally expected. Poor design and improper installation led to low performance figures in many of the early SHAC projects. Thanks to the information that was obtained from these projects and then disseminated, a great deal more is now known regarding the proper way to employ solar energy on buildings. Users are cautioned however, to take advantage of the excellent handbooks available and not repeat mistakes made in the past. Solar cooling systems especially are still in need of further refinement in the field.

II. INDUSTRY

Whereas 36.3% of the U.S. energy demand is for commercial and residential uses, 41.2% is used by industry as shown in Fig. 19. Of that amount, 68.4% is direct thermal use which presents a potential market for solar application.

Using solar energy to supply industrial process heat (IPH) offers several potential advantages when compared to solar heating and cooling applications:

- Loads are often constant throughout the year allowing for better use of solar energy.
- Industrial plants usually have maintenance crews which can attend to the solar energy systems.
- Large collector arrays have the potential for yielding economies of scale.
- The total potential impact on the nation's energy use is greater.

When compared to alternative industrial fuels, solar energy offers the advantages of being nonpolluting and not subject to outside supply interruptions. Lead times for the construction of solar energy systems are also reasonably short.

Of course, certain impediments to the use of solar energy in IPH also exist:

- Land availability. In most climates with high insolation, roofs may be inadequate for supporting collector arrays. Either added supports must be built or land must be used. In the latter case, commercial land is often expensive and scarce.
- Industrial effluents. In an industrial environment, contamination of collectors is a greater problem than for commercial or residential buildings. Concentrating collectors which require high specular reflectivity are particularly susceptible.
- Nonconstant energy source. The plant must be able to adapt to the variable solar energy delivery.

TABLE 2. SUMMARY OF SYSTEM COSTS

Application	Project	Total ^a System Cost, \$	Total ^b System \$/sq ft	Collector		Support Structure		Piping, Ductwork, & Insulation		Heating Cooling/ Equipment		Storage		Electrical & Controls		General Construction	
				\$/sq ft	% ^c	\$/sq ft ^d	%	\$/sq ft	%	\$/sq ft	%	\$/sq ft	%	\$/sq ft	%	\$/sq ft	%
Passive Heating	Kalwall	13,530	7.7	6.1	79	—	—	—	—	0.6	8	0.8	10	0.3	3	—	—
Process Hot Water	Aratex	18,240	29.0	11.7	40	2.8	10	10.4	36	—	—	2.4	8	1.3	4	1.0	3
	Iris Images	18,115	30.2	10.5	35	7.2	24	4.0	13	—	—	2.1	7	1.8	6	4.4	15
	Ingham Co.	337,260	36.0	10.3	29	11.2	31	11.2	31	—	—	1.2	3	1.7	5	0.8	2
	Hogate's	283,955	48.6	18.2	37	8.7	18	13.1	27	—	—	4.1	8	1.1	2	3.4	7
	Loudoun Co.	70,940	60.7	21.8	36	17.2	28	12.2	20	—	—	5.4	9	3.3	5	0.8	1
Average		—	40.9	14.5	35	9.4	23	10.2	25	—	—	3.0	7	1.8	4	2.1	5
Liquid Space Heating	Moseley	14,295	38.0	13.8	36	3.3	9	6.3	17	5.2	14	4.1	11	4.6	12	0.8	2
	Telex	462,305	43.2	17.3	40	6.6	15	13.9	32	1.0	2	1.5	3	2.0	5	0.9	2
	Billings	77,430	46.6	20.4	44	7.8	17	13.3	29	0.9	2	1.8	4	2.5	5	—	—
	Charlotte	249,195	60.8	18.0	30	5.9	10	24.8	41	0.2	< 1	3.3	5	3.3	5	5.1	8
	Blakedale	60,510	65.2	12.0	18	15.4	24	21.0	32	—	—	8.2	13	8.5	13	0.1	< 1
Average		---	50.8	16.3	32	7.8	15	15.9	31	1.5	3	3.8	7	4.2	8	1.4	3
Air Space Heating	Howard's Grove	53,300	22.6	13.4	59	2.4	11	3.2	14	—	—	2.7	12	0.9	4	—	—
	DuCat	252,435	36.1	21.9	61	9.3	26	3.5	10	—	—	—	—	1.4	4	—	—
	Aberdeen	62,595	49.7	24.8	50	1.3	3	13.1	26	—	—	5.6	11	3.3	7	0.9	2
	Scattergood	113,825	50.8	24.5	48	11.5	23	6.0	12	2.1	4	3.8	7	2.7	5	0.2	< 1
	Concord	118,740	68.4	18.6	27	25.7	38	12.3	18	—	—	5.2	8	6.2	9	0.4	1
Average		—	45.5	20.6	45	10.0	22	7.6	17	0.4	1	3.5	8	2.9	6	0.3	1
Space Heating & Cooling	Page Jackson	526,845	48.1	15.9	33	15.8	33	8.4	17	3.3	7	1.5	3	0.3	1	3.0	6
	Irvine	285,190	57.0	28.3	50	7.7	14	15.0	26	—	—	—	—	4.8	8	1.3	2
	Trinity	958,210	61.3	29.1	47	5.5	9	13.2	22	2.9	5	4.2	7	2.9	5	3.6	6
	Mt. Rushmore	130,705	75.8	21.2	28	13.9	18	16.9	22	8.6	11	3.6	5	6.6	9	5.0	7
	North Hampton	384,680	105.1	21.4	20	6.3	6	31.5	30	7.4	7	8.9	8	16.2	15	13.4	13
	Columbia Gas	352,260	118.3	53.0	45	10.2	9	17.1	14	—	—	4.5	4	14.6	12	18.9	16
	Radian	42,150	120.4	37.4	31	15.7	13	30.9	26	14.4	12	7.7	6	9.8	8	4.8	4
	Reedy Creek	625,985	163.0	108.4	67	4.7	3	18.9	12	4.7	3	10.9	7	5.6	3	10.4	6
Average		—	93.6	39.3	42	10.0	11	19.0	20	5.2	6	5.2	6	7.6	8	7.6	8
Total Average		—	60.1	24.1	40	9.0	15	13.4	22	2.1	3	3.9	6	4.4	7	3.3	5

^aAll costs in 1977 \$, costs include overhead and profit.

^cPercent of total system cost.

^bDollars per square foot of net collector area.

^d— No category costs incurred.

- Availability of conservation alternatives. Many plants have simple and inexpensive opportunities for energy conservation which should precede any commitment to solar. These include the use of waste heat from high-temperature processes to supply low-temperature processes (such as boiler feedwater preheat).
- Cost. Industry often requires payback periods of less than five years. Solar energy systems are currently too expensive to provide such paybacks, but the trend is toward shorter payback periods.

Figure 19. U.S. Energy Demand by Sector.

The suitability of solar energy in a particular application depends upon a number of factors such as climate, economics, process temperature, and availability of space. In 1977, ERDA (the predecessor of DOE) commissioned two major studies (by InterTechnology Corporation and Battelle Laboratories) to determine the potential application of solar energy in IPH [7,8]. Figure 20 shows one result from the study done by InterTechnology Corporation (ITC). A computer simulation compared the performance of a flat plate collector system designed to deliver 1,000 gal (3,785 L) of 140°F (60°C) hot water per day in various cities in the United States. This took both insolation and ambient temperature into account. As one might expect, the Southwest is an ideal location for such a plant.

Table 3 shows where industry is located. The states are compared on the basis of fuel sales. Eighty percent of the energy used by industry is consumed in 13 states. California, which is an excellent candidate for solar energy is ranked fifth with 6% of the total. Texas, which is ranked first, has some very good areas for solar application.

Figure 20. Regional Performance of a Reference IPH Hot Water System.

Table 3. LOCATION OF INDUSTRY
(80% in 13 States)

	% of U.S. Total
Texas	22
Louisiana	10
Pennsylvania	9
Ohio	9
California	6
Illinois	6
Michigan	6
Indiana	5
New York	2
Alabama	2
New Jersey	1.5
West Virginia	1.5
Wisconsin	1.5

Whether solar energy is practical depends to a great extent on which fuel it must compete against. Table 4 shows the percentages of each type of fuel input to the industrial sector in 1976. Oil and natural gas, which can be expected to rise in price, accounted for 68.8% of the energy use. Coal can be expected to remain fairly inexpensive (although the cost and extent of use will depend greatly on pollution requirements). Electricity will remain expensive unless it is generated by coal.

**Table 4. FUEL USE BY
INDUSTRIAL
SECTOR (1976)**

	%
Coal	18.0
Oil	29.2
Natural Gas	39.6
Electricity	13.2

The temperature at which energy is used is also of vital importance in assessing the solar option. The higher the temperature needed, the greater will be the extent to which solar collectors lose their collected heat to the outdoor environment and thus the lower will be their efficiency. ITC plotted the percentage of total IPH consumption versus process temperature. As shown in Fig. 21, 27% of the energy consumed is at temperatures below 550°F (275°C)—the approximate limit for current production collectors.

Figure 22 shows the energy use of major industrial groups. Note that 80% of the energy is used by six major industries. Currently, detailed case studies of individual industrial plants are being performed at the Solar Energy Research Institute (SERI) to more accurately determine application feasibility.

Collectors

The same types of collectors used in SHAC applications (flat plates, evacuated tube, line focus) have also been used in industrial applications. There are several others, however, that are useful in supplying industrial process heat: solar ponds at the low end of the temperature scale and point focus and central receivers at the high end. These are discussed briefly below.

Solar Ponds

These are basically of two types. Shallow ponds developed by Lawrence Livermore Laboratory consist of bags of water which are heated by the sun during the day and drained at night. Because they are mounted horizontally they perform best at lower latitudes. They can supply heat at temperatures below 125°F (50°C) at relatively low cost.

Salt gradient ponds developed extensively in Israel can supply water at considerably higher temperatures. These ponds work on the principle that solar heated water will dissolve salt and remain in the bottom of the pond by virtue of its

higher density. A salt pond has the advantage of supplying long-term storage in addition to serving as a solar collector. Studies are currently being performed on how best to achieve and maintain pond stability.

Figure 21. Distribution of IPH Requirements by Temperature.
SOURCE: Ref. 7.

Figure 22. Process Heat Requirements in Major Industrial Groups.

Point-Focus Receivers

Concentrators can achieve good efficiency at high temperatures because of the reduced receiver area for heat loss. Parabolic dish collectors take this advantage to the extreme by focusing sunlight onto a point. Temperatures of up to 2000°F (1095°C) can be supplied. This requires two-axis (azimuth and altitude) tracking of the sun. Like the line focus collectors, point focus collectors can use only direct radiation. Because of collector shape and tracking requirements, they do not use land space as efficiently as the previously mentioned collectors. However, at temperatures much higher than 500°F (260°C), they and central receivers are the only choices.

Central Receivers

By using a centrally located receiver on a tower surrounded by a field of carefully aimed individual reflectors (called heliostats) very high concentration and thus high temperatures can be achieved. Since all of the energy is transmitted to one central receiver in the form of light, the piping losses associated with distributed receivers are eliminated. Drawbacks include tower support costs, rigorous tracking requirements, and use of only direct insolation. Central receivers are still in an early development phase.

Solar Applications in IPH

The three main areas of solar application in industry are in the areas of:

- Process hot water
- Drying/dehydration
- Process steam.

Hot water is used in large amounts between 120° and 212°F (50-100°C) for cooking, washing, bleaching, and anodizing and represents about 2% of the IPH demand or 0.2 quad (1 quad = 10^{15} Btu). The preheat of boiler feedwater accounts for another 3 quads, but this can often be supplied by associated higher temperature waste heat. Either water can be heated directly in a collector loop, or a separate fluid can be used in conjunction with a heat exchanger. The latter approach can minimize freezing and corrosion problems but results in somewhat higher collector temperature and thus in reduced efficiency.

An example of an industrial process heat hot water system is shown in Fig. 23. This particular system supplies over 400 gal/min (1,514 L/min) of hot water in the range of 130°F to 180°F (55° to 83°C) to the York Building Products concrete block curing plant in Harrisburg, Pa. The collector array consists of 9,216 ft² (829 m²) of multiple-reflector type linear concentrators. A shell-and-tube heat exchanger is used to transfer heat from the water/ethylene glycol collector loop to the process water. A unique feature of this application is that the large underground concrete curing area or "rotoclave" contains about 50,000 gal of water and serves as built-in storage.

Figure 23. York Building Products Solar Hot Water System.

Drying and dehydration consume about 1.4 quads supplied as hot air below 350°F (177°C). Most of this is used for crop drying. The two most common ways to supply solar heated air are to heat air directly in the collectors or to heat a liquid in collectors and use a liquid-to-air heat exchanger.

An example of the first type of system is shown in Fig. 24. In this system, 21,000 ft² (1,890 m²) of air collectors supply 140°F (60°C) air to a prune and raisin drying tunnel at the Lamanuzzi and Pantaleo Foods plant in Fresno, Calif. A 14,000 ft² (420 m²) rock bin is used for storage. A unique aspect of this plant is a heat recovery wheel which transfers heat from the tunnel exhaust to the collector array inlet. Although this raises the collector array temperature and thus lowers collector array efficiency, the heat recovered more than makes up for the lowered collector efficiency. The heat recovery wheel has a payback period of less than 1 year, and its success emphasizes the importance of preceeding solar applications with conservation alternatives.

An example of heating water in order to supply hot air is shown in Fig. 25, which illustrates the system at the J. A. LaCour lumber drying kiln in Canton, Miss. At this plant 2,500 ft² (225 m²) of flat-plate collectors heat water to 140°F (60°C), which then supplies hot air to two hardwood lumber kilns via finned-tube heat exchangers. Although this system results in higher collector temperatures than in a direct air approach, pumping power for the liquid loop is generally less than fan power for an air loop. To increase collected energy at the LaCour plant, 2,400 ft² (216 m²) of reflectors are included in the collector array.

A third alternative for using solar heat in drying should be mentioned. Rather than using collectors at all, drying houses can be constructed in such a fashion that sunlight impinges directly upon the product to be dried. This approach results in relatively low temperatures and long drying times and will generally require that the product be spread out over a larger area. However, it can be a cost-effective approach.

Figure 24. Lamanuzzi & Pantaleo Foods Solar Air System.

Figure 25. LaCour Lumber Kiln Solar Hot Water-to-Air System.

Steam usage represents about 6 quads of energy consumption, 80% of which is below 350°F (177°C). Three possible ways to supply steam with solar collectors are:

- Use of a high-temperature fluid in the collectors with heat transferred to an unfired boiler
- Circulation of pressurized water in the collectors with subsequent flashing to steam in a flash tank
- Boiling of water in collectors.

The first type of system is shown in Fig. 26. In this example Therminol 55® (heat exchange oil) is heated to 475°F (246°C) in an array consisting of 10,000 ft² (900 m²) of parabolic trough collectors. The hot Therminol then boils water in an unfired boiler with steam supplied at 125 psi. The particular system shown here is being built for the Southern Union Oil Refinery in Hobbs, N. Mex.

Figure 26. Solar Steam Supply Using an Unfired Boiler.

In designing the solar system for the oil refinery, the flash system shown in Fig. 27 was considered as an alternative. In that system, water would be heated directly to 477°F (247°C) and 600 psi in the collector loop and then flashed to steam. This eliminates the need for an expansive unfired boiler and can provide more collected energy since the temperature difference across the heat exchanger is eliminated. On the other hand, freeze protection is required, and considerable pumping power must be provided to supply the pressure difference across the flash valve. A flash system similar in principle to the one shown is being built at the Ore-Ida Foods, Inc., french-fried potato plant in Ontario, Oreg.

The third alternative of boiling water in the collectors has not yet been attempted. Potential problems such as corrosion, tube burnout, and destructive temperature fluctuations must first be overcome.

Figure 27. Solar Steam Supply Using a Flash Tank.

Although steam is widely used in industry to transport heat, solar energy can probably be combined better with hot water. If hot water is used to supply heat to a process, solar collectors can be used without need for an unfired boiler and without having to suffer the disadvantages of a flash system. Thus, if solar energy is being considered for a new plant, some consideration should also be given to the use of pressurized hot water in place of steam.

INDUSTRIAL PROCESS HEAT FIELD TESTS

In an effort to advance the state-of-the-art in solar industrial process heat, the U.S. Department of Energy (DOE) has funded a number of field tests throughout the United States. These have been funded in cycles with each new cycle testing a different area for solar application: hot water [212°F, (100°C)], hot air, low-temperature steam [212°-350°F (100°-177°C)], and intermediate-temperature steam [350°-550°F (177°-275°C)]. In addition, two new cycles are currently being funded for large collector area [50,000 ft² (4,500 m²)] projects both above and below 212°F (100°C) in order to investigate economies of scale. A list of the projects, several of which have been mentioned earlier, is given in Table 5.

Much has already been learned from the existing field tests. Six projects that have been operating for a year or longer were the subjects of a report by the Solar Energy Research Institute [9]. System efficiencies have ranged from 8%-33% for the first year of operation. As newly designed projects benefit from the experiences of earlier field tests, reliability and performance can be expected to increase.

TABLE 5. DOE-SPONSORED INDUSTRIAL PROCESS HEAT FIELD TESTS

**CYCLE 1: LOW-TEMPERATURE HOT WATER/HOT AIR INDUSTRIAL
PROCESS HEAT FIELD TESTS (60°-100° C, 140°-212° F)**

Location	Process	Industrial Partner/ Contractor	Collectors	Array Size (m ²)	Collection Temp. (°C)	Designed Annual Energy Delivery (GJ/m ²)	Status
HOT WATER							
Sacramento, Calif.	Soup can washing	Campbell Soup Co./ Acurex Corp.	Flat plate and parabolic trough	681.4	66	3.41	Operational (Nov. 1977)
LaFrance, S.C.	Textile dyeing	Riegel Textile Corp./ General Electric Co.	Evacuated tube	620.6	132	2.38	Operational (June 1978)
Harrisburg, Pa.	Concrete block curing	York Building Products, Inc./ AAI Corp.	Multiple reflector	856.2	57	1.85	Operational (Sept. 1978)
HOT AIR							
Gilroy, Calif.	Onion drying	Gilroy Foods, Inc./ Trident Engr. Assoc.	Evacuated tube	552.8	99	4.46	Operational (Sept. 1979)
Decatur, Ala.	Soybean drying	Gold Kist, Inc./ Teledyne-Brown Engr.	Flat plate	1,217.4	60	3.20	Operational (May 1978)
Canton, Miss.	Kiln drying of lumber	J. A. LaCour Kiln Services, Inc./ Lockheed Missiles and Space Co.	Flat plate	234.1*	61	4.05	Operational (Nov. 1977)
Fresno, Calif.	Fruit drying	Lamanuzzi & Pantaleo Foods/ Calif. Polytechnic State U., San Luis Obispo	Flat plate	1,951.0	63	1.25	Operational (Aug. 1978)

*plus 223 m² reflectors

**CYCLE 2: LOW-TEMPERATURE STEAM INDUSTRIAL PROCESS
HEAT FIELD TESTS (100°-177° C, 212°-350° F)**

Location	Process	Industrial Partner/ Contractor	Collectors	Array Size (m ²)	Steam Conditions	Designed Annual Energy Delivery (GJ/m ²)	Status
Pasadena, Calif.	Commercial laundry	Home Cleaning and Laundry/ Jacobs-Del Solar Systems	Parabolic trough	603.5	0.86 MPa 171°C	2.83	Construction
Sherman, Tex.	Gauze bleaching	Johnson & Johnson/ Acurex Corp.	Parabolic trough	1,070.2	0.86 MPa 174°C	1.39	Operational (Jan. 1980)
Bradenton, Fla.	Orange juice pasteurizing	Tropicana Products, Inc./ General Electric Co.	Evacuated tube	929.0	1.03 MPa 177°C	3.07	Construction
Fairfax, Ala.	Fabric drying	West Point Pepperell/ Honeywell, Inc.	Parabolic trough	772.3	0.58 MPa 158°C	1.50	Currently being refurbished

**CYCLE 3: INTERMEDIATE-TEMPERATURE STEAM INDUSTRIAL
PROCESS HEAT FIELD TESTS (177°-288° C, 350°-550° F)**

Location	Process	Industrial Partner/ Contractor	Collectors	Array Size (m ²)	Steam Conditions	Designed Annual Energy Delivery (GJ/m ²)	Status
Dalton, Ga.	Latex production	Dow Chemical/ Foster-Wheeler Devlp. Corp.	Parabolic trough	922.5	186°C 1.14 MPa	2.86	Construction
San Antonio, Tex.	Brewery	Lone Star Brewing Co./ Southwest Research Inst.	Parabolic trough	877.9	177°C 0.96 MPa	3.84*	Construction
Ontario, Ore.	Potato processing	Ore-Ida Co./ TRW	Parabolic trough	884.4	214°C 2.07 MPa	2.27	Construction
Hobbs, N. Mex.	Oil refinery	Southern Union Co./ Monument Solar Corp.	Parabolic trough	936.5	193°C 1.27 MPa	3.99	Construction

*collector output

**TABLE 5. DOE-SPONSORED INDUSTRIAL PROCESS HEAT FIELD TESTS
(concluded)**

**LOW-TEMPERATURE COST-SHARED INDUSTRIAL
PROCESS HEAT FIELD TESTS (to 100°C, 212°F)**

Location	Process	Collectors	Contracting Team	Array Size (m ²)	Delivery Temp. (°C)	Designed Annual Energy Delivery (GJ/m ²)	Status
Santa Isabel, Puerto Rico	Fruit juice and nectar pasteurization	Evacuated tube	Nestle Enterprises/ General Electric/ CEER/OMB A/E	4,645	99	2.01	Design
Santa Cruz, Calif.	Leather tanning and finishing	Flat plate	Salz Leathers/ Pacific Sun/ Chilton Engr.	3,666	27	2.58	Design
Oxnard, Calif.	Sodium alginate processing	Flat plate	Stauffer Chemical/ Wormster Scientific/ Desert Research Inst.	3,530*	52	7.44	Design
Des Moines, Iowa	Meat processing	Flat plate	Team, Inc. of Va./ Oscar Mayer/ Univ. of Wisconsin	3,746	82	2.99	Design
Shelbyville, Tenn.	Poultry processing	Linear fresnel	Tyson Foods/ Lockheed	4,682	60	3.32	Design

* Plus 4100 m² of reflectors.

**CYCLE 4: INTERMEDIATE-TEMPERATURE COST-SHARED INDUSTRIAL
PROCESS HEAT FIELD TESTS (100°-288°C, 212-550°F)**

Location	Process	Contracting Team	Collectors	Array Size (m ²)	Fluid Conditions	Designed Annual Energy Delivery (GJ/m ²)	Status
Fort Worth, Tex.	Corrugated board production	Bates Container/ BDM	Parabolic trough	3,226	Steam 227°C 1.03 MPa	2.60	Construction
San Leandro, Calif.	Pressurized hot water for washing	Caterpillar Tractor/ SWRI	Parabolic trough	4,682	Water 113°C 0.2 MPa	3.05	Construction
Pepeekeo, Hawaii	Cane processing and electricity	Hilo Coast Processing Co./ Team, Inc.	Parabolic trough	1,097	Steam 204°C 1.14 MPa	3.48	Design only
Haverhill, Ohio	Chemical plant-polystyrene	U.S.S. Chemicals/ Columbia Gas/ H. A. Williams and Assoc.	Parabolic trough	4,682	Steam 227°C 1.03 MPa	1.62	Construction

Although six projects provide a limited statistical basis on which to make generalizations, some basic conclusions can be drawn that should prove useful in future projects. These are:

- Although performance of solar collector arrays in first generation IPH systems has been lower than predicted, collector arrays have exhibited high availability, i.e., have been basically reliable. Degradation of absorber surfaces and glazings is still relatively common.
- Inadequate utilization of solar energy by the industrial processes has been a major problem. Certain adjustments in plant operation schedules, hardware, and control logic are often needed to optimize the use of a solar energy system.
- Problems similar to those encountered in the solar heating and cooling of buildings program occur in IPH applications. Better education in system

design is needed to prevent the occurrence of problems such as thermal shocking of evacuated tube collectors, heat exchanger freezing due to thermosyphon heat loss, improper pump selection, etc.

- Parasitic power requirements have proved to be major contributors to low system performance in those systems employing air collectors.
- Both operational and overnight piping losses must be minimized in solar IPH applications.
- Data acquisition systems have generally been very unreliable.
- Solar energy application to industrial process heat is not yet cost-effective when the typical payback periods required by industrial owners are considered. Although industrial managers are concerned with fuel curtailments, most do not yet view solar energy as a profitable investment.
- Environmental contaminants of an industrial environment can seriously affect solar collector performance.
- Energy conservation opportunities are abundant in industry, and many have much more rapid payback periods than solar energy systems. Just as in the solar heating and cooling of buildings, energy conservation should precede solar implementation.
- In some applications, solar energy may improve the quality of a final product in addition to saving fossil fuel.

More details on the low-temperature field tests including total costs can be found in Ref. 3.

In an effort to provide for better designs of solar IPH systems, SERI has published Design Considerations for Solar Industrial Process Heat Systems [10]. This document discusses a large number of items which should be addressed in designing an IPH system. To provide a quantitative step-by-step design manual, SERI is now preparing a Solar Industrial Process Heat Systems Design Handbook which should be completed in early 1982.

The future of solar energy in industrial process heat depends on a number of factors. Increased costs of fossil fuel will certainly make solar more attractive. Unavailable or interrupted fossil-fuel supplies would have an even greater impact. As collectors are mass produced, costs can be expected to drop substantially. Improvements in both collector efficiency and reliability will also accelerate solar implementation. Finally, cost studies have shown that government tax incentives can play a large part in bringing solar costs in line with what industry is willing to pay. (Details on the economics of solar IPH systems can be found in Ref. 11.)

Solar Total Energy Systems

Some attention has been paid to using solar thermal collectors to supply not only low-grade thermal energy for process heat but high-grade electrical energy as well. One example is a DOE-funded project being built in Shenandoah, Ga [12]. It consists of a collector array containing 114 diameter parabolic dish collectors designed to supply 12×10^{12} J of energy per year at 400°C.

The high-temperature collector fluid generates steam in an unfired boiler, which then passes through a turbine generator to yield 400 kW of electricity. Steam exiting from the turbine is used to preheat boiler feedwater and supply an industrial process in a knitwear factory. Finally, hot water from the condenser is used to supply building heating and run an absorption chiller. Solar storage is provided by three "trickle oil" tanks containing a mixture of heat transfer oil and iron ore.

Scheduled to become operational in late 1981, it is hoped that the Shenandoah project will provide important information regarding how a solar total energy system can interface with an electric utility.

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