Solar Thermal Systems in Industry

D.J. ALLEN and A.C. GANGADHARAN, Foster Wheeler Solar Development Corporation, Livingston, NJ

ABSTRACT

A significant portion of the demand for industrial process heat can be met with solar energy. Whether this energy source is widely used will depend not only on its economic attractiveness, but also on the ease with which solar thermal systems interface with the remainder of the industrial plant. Foster Wheeler has recently designed solar thermal systems to supply hot water and process steam to industry and has nearly completed the construction of one of these. Drawing on this experience, this paper discusses selection of solar technologies that can best satisfy the user's energy requirements and minimize interfacing problems.

INTRODUCTION

This paper examines the potential market for solar industrial process heat, describes some of the technologies by which solar thermal energy can be delivered and illustrates some factors that will influence the viability of solar thermal energy in industry.

SOLAR THERMAL ENERGY IN INDUSTRY

The use of solar thermal energy to provide process heat to industry is particularly attractive for the following reasons: (a) the demand for process heat is enormous, requiring an estimated 20% of total U.S. energy consumption (1,2). Of this, 80% is now provided by premium fuels (oil and gas) (3); (b) industrial process heat requirements are either steady throughout the year or else rise in summer (as in many food processing industries), thus allowing full use to be made of all collected solar energy; (c) maintenance and operation of solar thermal systems should pose few problems to facilities with experienced maintenance personnel; (d) no costly thermal energy storage is required as conventional back-up units are available for use at night or in other periods of low insolation; (e) with a large demand for process heat, economies of scale can be achieved both in the manufacture and installation of solar thermal systems. These economies will further assist the development of solar thermal energy.

Industry uses process heat in many applications over a wide temperature range. These applications encompass both the use of hot (120 F) water in food and can washing, and direct firing as in the processing of glass, chemicals, ceramics and metals at temperatures up to 1,800 F. Although solar thermal energy can be delivered across this entire temperature range, those solar thermal systems under extensive development at this time are best suited to deliver steam, water, gases, or other heat transfer fluids at temperatures below 600 F.

SOLAR THERMAL TECHNOLOGIES

The technologies used in collecting solar thermal energy for delivery as process heat can be divided into 5 categories: (a) nontracking, nonconcentrating receivers (e.g., flat plate collectors); (b) nontracking, semiconcentrating receivers (with cusp or V-trough collector backings); (c) line-focusing, single-axis tracking collectors (e.g., parabolic trough collectors); (d) distributed, 2-axis tracking, point focusing collectors (e.g., parabolic dish collectors); and (e) central receivers with 2-axis tracking heliostats (mirrors). The temperature range over which these technologies are applicable varies (Fig. 1). Essentially, this range is determined by the optical concentration ratio achieved by the collector: the concentration ratios of flat plates, parabolic troughs and central receivers (or parabolic dishes) are 1:1 (or no concentration), 50:1 and 1,000:1, respectively.

Nontracking collectors are characterized by simplicity of construction and operation. They can operate efficiently at temperatures below 200-350 F (100-175 C) and are now commercially available in quantity. With further refinements, these collectors will achieve the long-term reliability required of a solar thermal system.

Tracking collectors are at earlier stages of development. Before describing them further, it is appropriate to mention some design elements common to these collectors: (a) a highly reflective mirror surface resistant to environmental effects; (b) a mirror support capable of providing sufficient rigidity to prevent warping under anticipated wind loadings; (c) adequate sun-sensing and tracking to ensure optimal focusing; and (d) a solar energy receiver with high absorptivity and low emmissivity capable of withstanding high temperatures. These elements are the subject of intensive research and development efforts.

Of the tracking collectors, parabolic troughs (Fig. 2, A and B) have been extensively and successfully demonstrated, delivering process heat at temperatures below 550 F. Declining efficiencies, the degradation of heat transfer fluids and the possible instability of the receiver's black chrome coating limit the use of parabolic trough collectors at higher temperatures at present.

Parabolic trough collectors have been described as having the greatest commercial viability (6). This statement is based on their current development status, their ability to deliver steam at temperatures and pressures that meet over

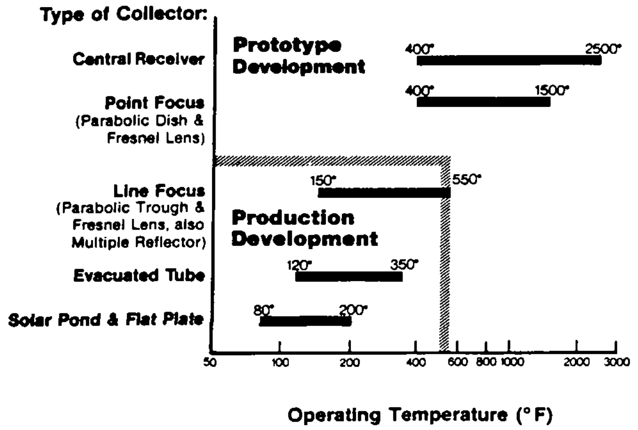


FIG. 1. Operating temperature ranges for solar thermal collectors (4).

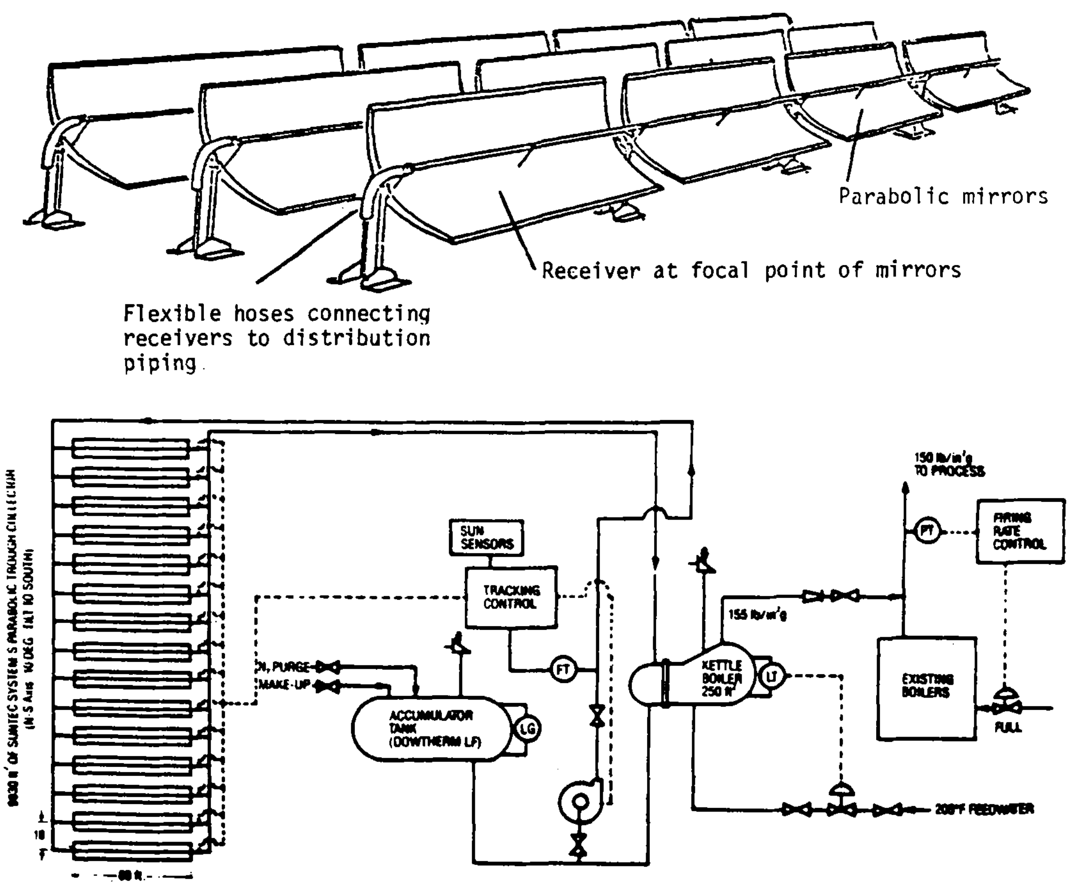


FIG. 2. (A) Parabolic trough collectors; (B) parabolic trough collector solar thermal system, designed and built by Foster Wheeler at the Dow Chemical Company's Dalton, Georgia, facility for the DOE (5).

80% of industrial requirements (1), and the fact that, excluding design costs, the capital and operating costs of parabolic trough solar thermal systems are proportional to the size of the collector field, thus allowing such systems to be equally viable in large and small sizes.

Recent solar thermal systems using parabolic trough collectors appear to be operating well; the low efficiency and unreliability that plagued earlier systems having been mostly resolved.

Parabolic dishes represent a point focusing, distributed receiver technology (Fig. 3). They offer a high optical performance, the capability of operating at high temperatures, an inherent modularity, and thus, considerable flexibility in their spatial arrangement. Their potential for power generation is particularly strong in that, by fitting each receiver with a Rankine, Brayton or Stirling engine-generator assembly, the high temperature capability of these collectors can be used without the need to distribute heat transfer fluids among the dishes. The development of advanced batteries will further enhance the viability of point focusing distributed collector systems. Accordingly, parabolic dishes have been ranked as being a most likely choice for using solar thermal energy in electrical power generation in facilities of less than 10 MWe.

While such a development would certainly facilitate the development of parabolic dish collectors, as with other distributed collector systems, their use to provide low-cost industrial process heat is limited by the necessity of carrying a heat transfer fluid between its point of application and the collector field. Similar considerations prevent the use of parabolic trough collectors in meeting high-temperature, direct process heat requirements.

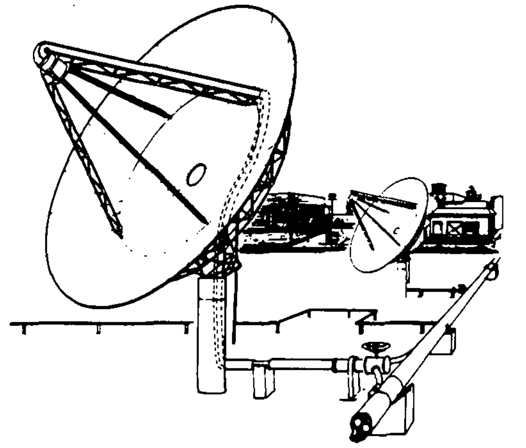
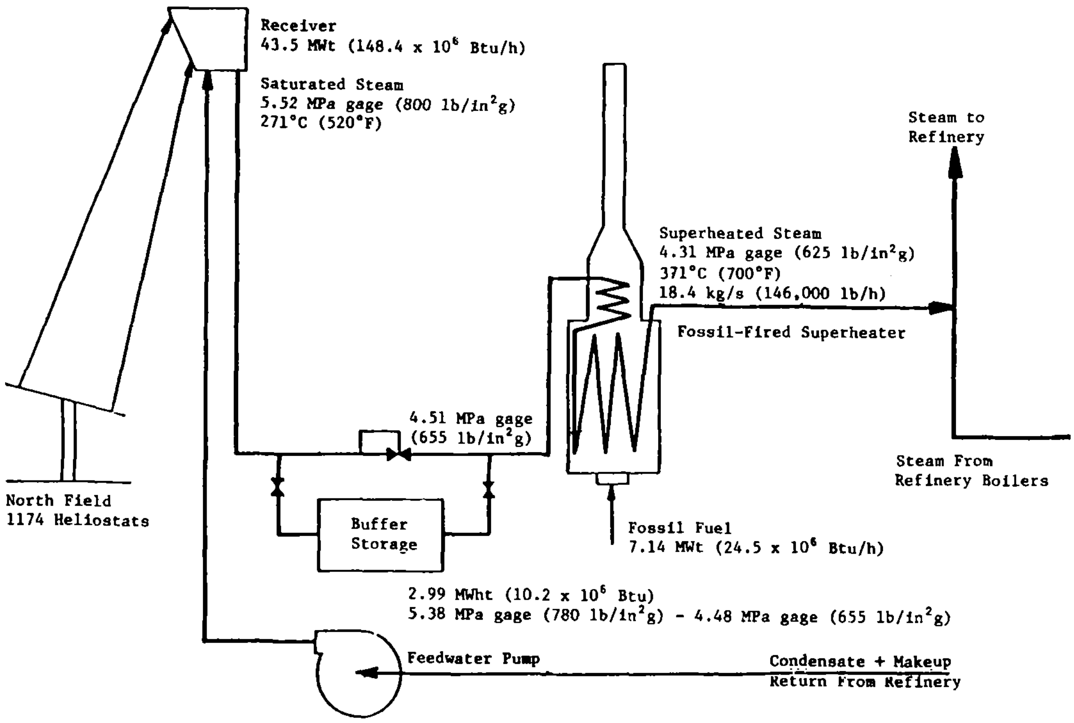


FIG. 3. Parabolic dish collectors supply solar industrial process heat (7).

Central receiver systems (Fig. 4) have applicability both in oil refining and other manufacturing operations, in enhanced oil recovery, and in central power stations. Larger systems (greater than 10 MWe) are particularly cost-effective as the installed cost of the receiver and associated equipment is relatively insensitive to the size of the heliostat (mirror) field.

Though future developments may call for use of solar energy in photochemical, photoelectrochemical, thermochemical and thermoelectrochemical conversion processes (8) directly within the receiver, in the immediate future,



Note: Figures shown are for peak output.

FIG. 4. Schematic of central receiver solar thermal system. Design was prepared by Foster Wheeler Development Corporation for the Provident Oil Company's refinery.

central receiver systems will likely be used to generate steam for use in Rankine cycles or in processes. Several receiver concepts are being investigated, including water/steam and molten salt or liquid metal receivers. The former are simple and inherently safe, the latter have favorable heat transfer characteristics that allow for compact receivers and heat exchangers and improved efficiencies. The problems associated with central receiver systems are largely those of severe thermal cycling, heliostat control and the high current cost of heliostats.

APPLICATION OF SOLAR THERMAL ENERGY

Successful use of solar thermal energy in industry will likely require the careful selection of location and application. The location chosen should be one with high insolation and high ambient temperatures to maximize the delivery of energy from the solar thermal system. Adequate land or roof space should be available close to the process heat delivery point. Furthermore, the location must be one with low air pollution levels to diminish the degradation of collector surfaces and the resulting impairment of system performance.

Applications chosen for solar thermal systems must also be selected carefully. Such applications must allow for both the diurnal and seasonal variations in solar energy incident upon the collectors and also the possibility that cloud cover or strong winds might interrupt the delivery of solar thermal energy. To maximize the useful energy delivered by the solar thermal system, the delivery of this energy must be acceptable whenever that energy is collected, and preferably to be so without necessitating the installation of costly thermal storage. Essentially, then, solar thermal energy is best used in continuously operating processes in which the control of the temperature or the rate of heat delivery from the solar thermal system is not critical. Such processes are those that do not require the scheduled delivery of energy, that can respond quickly to or compensate for fluctuating deliveries of solar thermal energy, or that incorporate a solar thermal system that contributes only a small portion of the process energy required. Foster Wheeler has prepared designs for 3 such steam generating solar thermal systems (5,9,10). The first (10) was for solar thermal enhanced oil recovery operations in which it is assumed that any steam generated will simply be immediately injected into oil bearing strata. In this instance, no delivery schedule is required. The second provided process steam for a refinery (9), in which pressurized water buffer storage provides continuity in steam generation until fired boilers take the load, should insolation fall abruptly. In a third design for a system that generates 155 psig steam for a latex plant (5), the peak rate of solar thermal energy delivery is about 30% of the minimal process heat demand. Therefore, even if the delivery of energy from the solar thermal system is suddenly curtailed, the conventional steam generator could pick up the load with only a small reduction in steam pressure, a reduction that is within the tolerance of the process.

In these 3 designs, strategies that allow the handling of fluctuations in the output of solar thermal energy were incorporated. The absence of such strategies will likely lead to severe problems or inefficiencies in the use of solar energy.

MARKET POTENTIAL FOR SOLAR THERMAL ENERGY IN INDUSTRY

Various studies have estimated the potential market for solar thermal energy in industry to lie between 20 and 35% (2) of the total required process heat by the year 2000. Recently, these estimates of the potential market have been questioned. A study of the refinery industry by May (11) concluded that low-temperature heat requirements in refining had been significantly underestimated. Some recent studies (12,13), however, tend to diminish estimates of the total potential for solar thermal energy in industry. They argue that conservation, the cogeneration of electric power and process heat, and the substitution of coal or biomass for oil and natural gas will all serve to limit the market for solar thermal energy. These new studies do not, however, negate the fact that the potential market for solar industrial process heat is enormous. Ultimately, the penetration of this market achieved by solar thermal systems will be determined by their cost effectiveness, a topic we will discuss later. Other factors will also be important. The extensive use of solar energy will require a favorable industrial environment: the presence of an infrastructure for installing and supporting such systems; the removal of regulatory barriers; and the acceptance of life-cycle costs as a basis for decision-making. The availability of front-end capital is also a matter of concern.

The delays in establishing an environment that is conducive to solar thermal energy when coupled with the present costs of solar thermal energy will slow the penetration of solar thermal energy into the industrial process heat market. Initial commercial systems will likely be in highly specific, highly favorable applications.

COST OF SOLAR INDUSTRIAL PROCESS HEAT

At present, solar thermal energy is not cost-competitive with conventional fuels (Table I). To redress this situation, intensive efforts are underway to improve the efficiency and reliability with which solar thermal systems operate and to reduce the capital and operating costs of such systems. Efficiencies will be enhanced through research to improve the reflectivity of mirrors, and to diminish heat losses from the receiver and the heat transfer fluid distribution system. Cost will be reduced by the design of low-cost equipment that is adaptable to mass production, preassembly (thus avoiding labor-intensive field work), and modularization (thus diminishing repetitious design work).

For parabolic trough collector solar thermal systems, efforts to reduce the cost of energy delivered include improving mirror surfaces, using the automobile industry's expertise and experience for the mass production of collectors (15), improving the design approaches to ensure that collector system and component designs are adequate, but not excessive, and introducing modular solar thermal system designs (16). Though these efforts will undoubtedly reduce the installed cost of parabolic trough collector systems, much work remains to be done to bring the cost down within a competitive range. In particular, the costs of such conventional items as pipework, foundations, instrumentation and electrical wiring must be substantially reduced by adopting methods of prefabrication and assembly at the factory. At present, the cost of these items amounts to one-fourth to one-third of the total installed cost.

Other distributed collector systems will also benefit from such research. A study of parabolic dish collector solar thermal systems has indicated that cost savings of up to 45% can be achieved in the installation of thermal transport piping networks through the use of automated factory assembly and semi-automated field assembly techniques (7). As with the parabolic trough collector systems, these cost reductions in heat transfer fluid distribution systems will need to be achieved for parabolic dish solar thermal systems to be cost-competitive with oil and gas.

Central receiver solar thermal systems show considerable promise. With mass production of heliostats, it is predicted that such systems, when used to displace gas and oil, will offer acceptable rates of return to their owners without resorting to extraordinary incentives (9). It is unlikely, however, that even this most efficient solar thermal technology will compete effectively with coal consuming (9) or cogeneration facilities. However, given the proper incentives, the use of solar thermal energy by industry, even at this early time, can be rewarding.

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TABLE I

Cost of Solar Thermal Energy

System type and location	Purpose	Capital costs: $/ft² of collector aperture	Capital costs: $/10⁶ Btu delivered/yr	Delivered cost of energy ($/10⁶ BTU)[a]
Parabolic troughs				
10,000 ft² field, Dalton, GA (5)	155 psig steam for latex prod	98[b]	345[b]	66.6
250,000 ft² field, Edison, CA (10)	800 psig steam for enhanced oil recovery	61.6[c]	230[c]	35.5
Parabolic dishes				
140,000 ft² field, Edison, CA (14)	800 psig steam for enhanced oil recovery	41.1[d]	106.4[d]	24.2[d]
Central receivers				
712,352 ft² field, Mobile, AZ (9)	800 psig steam for an oil recovery	53.0[e] 38.8[f]	105.5[e] 77.2[f]	14.57[e] 8.47[f]

[a]Cost in 1980 dollars assuming a 15% discounted cash-flow rate of return, a 20% investment tax credit, a 50% tax rate, a 15-year depreciation period and equity funding.

[b]These costs are those actually incurred and include installation and checkout.

[c]This cost estimate has an accuracy of 5%. The estimate is based on quoted prices of commercially available equipment.

[d]These estimates are speculative.

[e]Estimated costs for the first plant assuming no existing heliostat mass production.

[f]Costs assuming mass production of heliostats underway.

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