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April 1980

The Use of Solar Energy to Produce Process Heat for Industry

Ken Brown

SERI

Solar Energy Research Institute
A Division of Midwest Research Institute

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FOREWORD

This paper was prepared as an invited presentation to the 30th Annual National Plant Engineering and Maintenance Conference in Chicago, Illinois. The presentation was made in a session entitled "The Solar Transition." Interest in the subject of energy conservation and renewable energy is almost universal among today's plant engineers, and it is particularly appropriate that time should have been given to the discussion of the role of solar thermal energy as industry begins a new decade.

Information contained in this paper has been generated from work performed in Task 3472 (Engineering Field Test Evaluation) and in Task 3473.30 (Solar IPH Cost and Cost Goal Analysis). We gratefully recognize the contributions of Mr. E. Kenneth May and Mr. Charles Kutscher who have contributed greatly to the understanding of industrial applications and of solar thermal IPH systems, respectively, through their work at the Solar Energy Research Institute.

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SUMMARY

The role of solar energy in supplying heat and hot water to residential and commercial buildings is familiar to many of us. On the other hand, the role that solar energy may play in displacing imported energy supplies in the industrial and utility sectors often goes unrecognized. The versatility of solar technology lends itself well to applications in industry; particularly to the supplemental supply of process heat of all kinds.

The realization of that potential will depend, however, on the identification of the most suitable applications and locations for industrial solar energy and the continued improvement in cost, durability, and reliability of solar equipment. The status of solar thermal technology for industrial process heat applications is surveyed in this paper, including a description of current costs and operating histories. Because the current status is unsatisfactory in view of the goals established by President Carter for solar industrial energy, this paper outlines the most important objectives to be met in improving system performance, reducing cost, and identifying markets for solar IPH. The effect of government tax policy will be of little impact until technical efficiency and cost effectiveness are significantly improved.

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INTRODUCTION

In a recent publication by the Harvard Business School, the attitude of industry toward production costs, and especially toward those costs associated with energy supply, is summarized in the following statement: "Industry is characterized by constant self-awareness. Ever greater effort goes into computing and comparing in order to better allocate resources, balance processes and improve products. Industry has a bottom line, and profits are its final test" (Stobaugh 1979). Indeed, as rapidly rising energy costs put a squeeze on profits, most industries have posted an enviable record in reduction of energy consumption.* While not every corporation can afford to be innovative, a significant number of corporations still find the resources to support the research and development necessary to alter energy consumption in production processes or to change the source of energy supply to those processes. This generally innovative attitude makes industry a fertile ground for the introduction of new energy supply technologies, such as solar energy.

From the perspective of the solar energy research community, industry has become an important focal area for one major reason: sheer size of demand. Manufacturing accounts for approximately 35% of the end-use demand for energy in the United States (1978)—a share which is nearly equal to total residential and commercial energy use and 1.3 times the total energy demand for transportation** (EIA 1980). The Department of Energy regards the possibility of displacing fossil fuel as a primary argument in favor of solar energy; the large demand of the industrial sector supports an emphasis on solar industrial applications. Potential solar supply to industrial energy needs could come in a variety of ways. For example, the term "solar energy" encompasses not only the direct use of the thermal energy of the sun, but also the direct use of photoelectric energy through solar cells and the indirect use of solar energy in the form of biomass or wind. These solar energy forms could supply industrial energy not only as heat, but as electric power, mechanical power, or synthetic fuels and feedstocks. Although certain technologies, such as biomass, have the potential for much broader and more significant impact than others, all may have applicability, separately or together, in specific markets.

Attention in this paper is devoted to direct solar thermal technologies and their application to industrial process heat. While solar thermal applications are certainly not the only feasible options being explored by industry and the government today, this program is perhaps the most active element of the federal industrial solar program and one for which at least preliminary results in actual field tests are available. The federal government is sponsoring an active program in the analysis and demonstration of this technology for industry in an attempt to move it from familiar and accepted ground in

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*According to Energy magazine, 3 April 1978; U.S. manufacturing concerns reduced energy consumption per dollar of value added by an average of 26% from 1971 to 1976 (P. 8).

**According to the Energy Information Administration (EIA), industry (including agriculture, mining, and heavy construction) consumed 29.247 quads (10^{15} Btu) of primary energy in 1978. Approximately 22.6 quads were consumed directly in manufacturing industries, SIC codes 20 to 39. Residential and commercial consumption was 28.582 quads and transportation consumption 20.614 quads, for a total of 78.443 quads consumed in the U.S during 1978.

residential use into the relatively untested territory of industry. An examination of past progress provides a worthwhile example of the many problems that will be encountered in the introduction of new technology to the industrial energy marketplace.

Can Industry Afford Solar Energy?

Needed: proven technology, process integration, a 10-year equipment lifetime, sufficient economic incentives, adequate financing capital, and performance guarantees for investors

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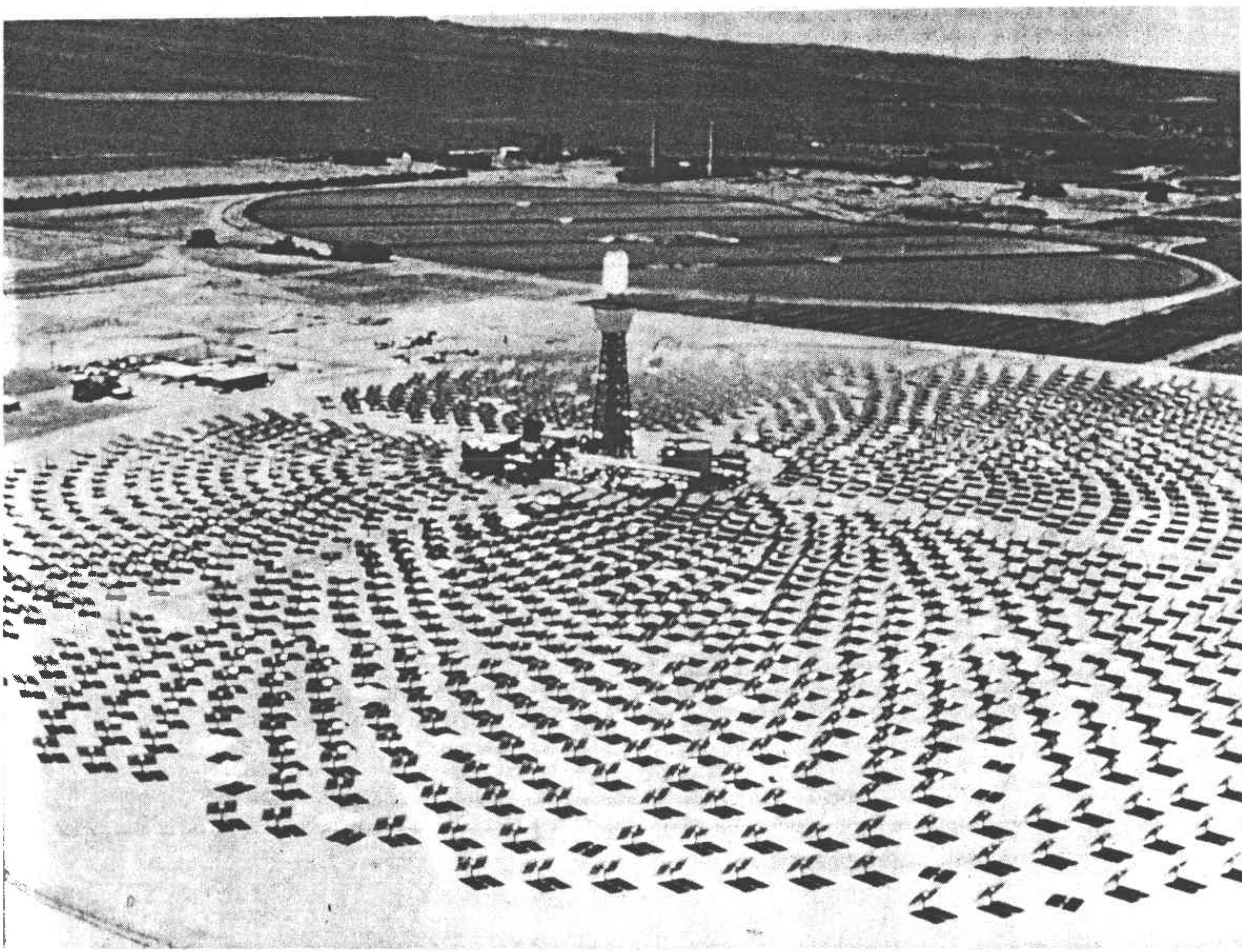


Solar energy is facing a difficult struggle. As a result of the worldwide depression and energy conservation measures initiated after the 1973 oil embargo, the demand for oil has been reduced and its cost has decreased. This has lessened, for the present, the urgency for developing solar energy in the U.S. and consequently the probability that solar energy will be introduced soon, on a large scale, appears less likely today than it was a few years ago. However, the long-term potential of solar energy and the need to develop its conversion technologies have not changed.

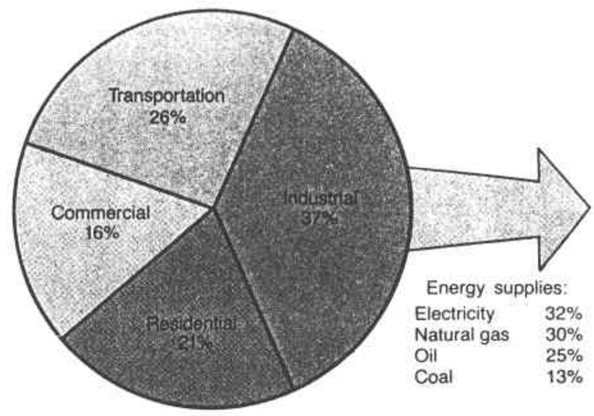
At the time of the 1973 energy crisis, two major views regarding energy policy existed. The "supply side" view assumed that energy demand growth is a priori desirable and necessary to nourish a healthy economy. Thus, the solution to the supply-demand imbalance according to this view was to increase the supply. The opposite view proposed reduction in demand as the solution, i.e., energy conservation.

In 1976 the National Academy of Sciences was asked to study this issue and the report by its Committee on Nuclear and Alternative Energy Systems (CONAES) was released in 1980 [1]. Perhaps the most significant contribution of CONAES to the energy debate was its unequivocal conclusion that "reducing the growth of energy demand should be accorded the highest priority in national energy policy."

The recent record of the industrial sector in energy conservation is most impressive. In 1974, the 10 most energy-intensive industries in the U.S. began a voluntary energy conservation program. By the end of 1978, these industries had reduced their combined energy use by 14 percent compared with a target improvement of 13 percent set for 1980. In addition to industry, it is estimated that residential conservation could save about half a million barrels of oil a day, and that the improved mileage in future cars will cut fuel consumption more than 30 percent before the end of the century.

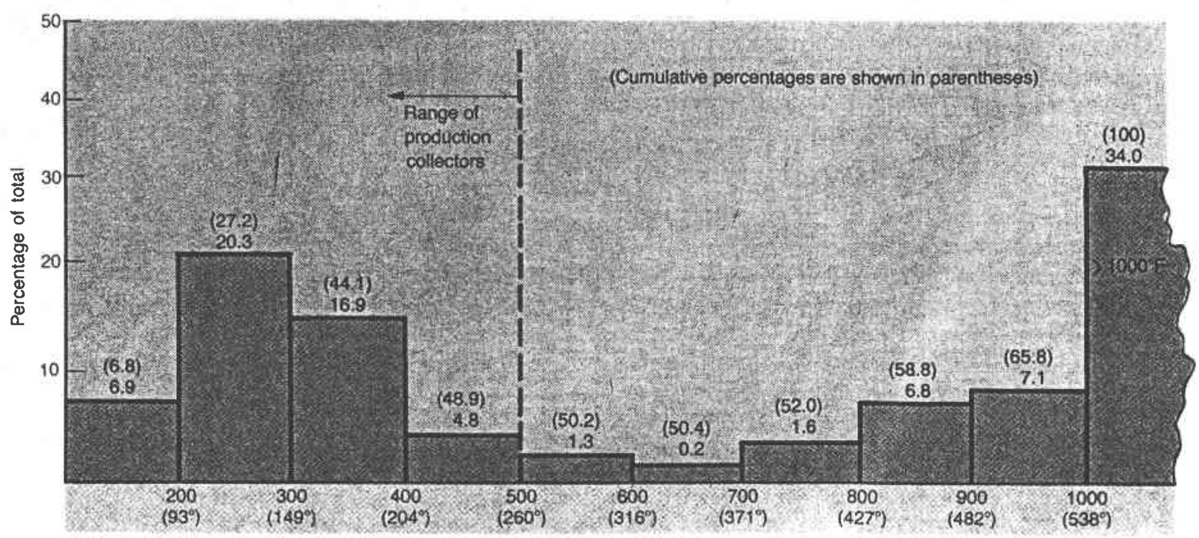
Predictions of U.S. energy needs for the year 2000 indicate that conservation measures will continue to reduce our energy consumption, but since conservation is not a net energy producer it will not be able to solve the energy problem in the long run. It does, however, postpone the time at which we will have to shift our energy supply from fossil fuels to other sources, and gives us a welcome respite during which we can plan an effective energy strategy, undertake the research necessary to improve the performance of conversion technologies, and reduce the cost of energy from renewable sources.

In a recent evaluation of the energy situation, the Office of Technology Assessment stated that: "A major transition between energy sources must occur during the next two or three decades because of the physical limits of supplies of low cost oil and natural gas. The transition may be painful, because all new energy sources are likely to cost more than the fuels they replace. The transition will be expensive, because most of the proposed new energy supplies will require large outlays of



Source: U.S. Bureau of Mines (Fuels & Energy Information Data); U.S. Bureau of Census (Annual Survey of Manufacturers, 1976)

Fig. 1 Distribution of industrial end-use consumption.



Source: F. Krawiec et al., July 1981

Fig. 2 Temperature distribution of industrial process heat demand.

capital—and therefore it is both likely and desirable that the transition will proceed slowly." [2]

Obviously, an undertaking of such magnitude as the transition from one energy source to another requires the active support of industry. The question is, therefore, "Can industry afford to use solar energy?"

The amount of solar energy potentially available on earth is many times larger than the current global energy use. However, to utilize this energy takes an enormous amount of capital, and before industry is willing to invest in a solar technology, its economical and technical feasibility must be demonstrated. Figure 1 shows the distribution of end-use consumption of energy by sectors divided into buildings, industry, transportation, and electric utilities. Some of the energy used by electric utilities is also supplied to industry, and it is estimated that the total percentage of industrial use is approximately 37 percent of the 73 Quads per year consumed in 1981 in the United States [3]. The major portion of this energy is used to supply process heat [4].

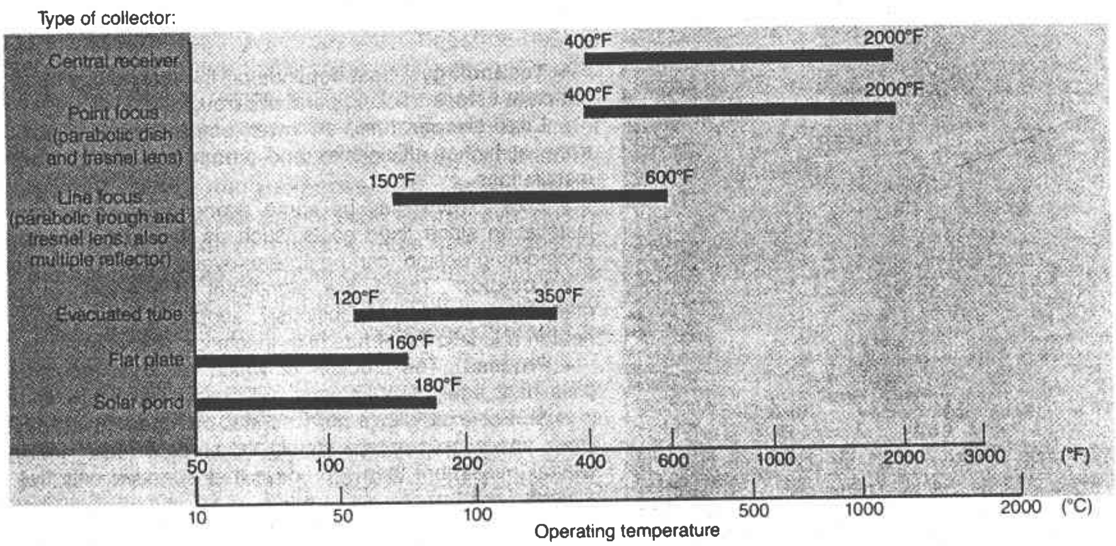
Industrial process heat is defined as the thermal energy required for the treatment and processing of manufactured goods. Solar energy is well suited to supply this heat because in industrial applications solar systems can operate at a much higher average annual efficiency than in seasonable applications such as residential heating, where the solar equipment is used only during the winter months. In industrial applications, the equipment can be properly matched to the end-use and be used all year round. Thus, a given capital investment in solar equipment for industrial use can deliver between two and three times more energy than an equivalent investment in home heating. Moreover, in industrial applications skilled service and maintenance are available, and because of the varied load requirements, the solar equipment can be closely matched to the temperature level demanded by the end-user. Finally, most industries operate only during the day when solar energy is available.

In 1977, a major study by Inter-technology Corporation [5] estimated that about 60 percent, or 18 Quads, of the total U.S. industrial consumption was used for process heat and that most of the energy for this end-use came from oil. Industrial process heat may be delivered via hot water, hot air, steam, a heat transfer fluid, or by direct transmission. To determine what type of solar technology is most suitable to supply this heat, it is necessary to determine what portion of it is used at what temperature.

Figure 2 shows the temperature distribution of industrial process heat demand while Fig. 3 shows the temperature ranges attainable by various types of solar collectors. Note that approximately 50 percent of industrial process heat is used at temperatures below 550°F, and can therefore be supplied by commercially available types of collectors such as solar ponds, flat-plate collectors, CPCs with evacuated tubes, and single-axis tracking parabolic troughs. It should also be noted that only 20 percent of the total industrial process heat is consumed between 550 and 1100°F, but that 30 percent is used at temperatures above 1100°F. The best solar technology for providing thermal energy from the sun at temperatures above 1100°F is a central receiver system, commonly known as the power tower.

This is an appropriate time to consider the potential of central receivers because the largest central receiver system in the world, a 10 MW electric power plant, called Solar One, has recently commenced operation at Barstow, Calif. [6]. Figure 4 shows the Barstow plant, which is considered a major step forward in solar thermal power technology. The solar plant produces steam used to drive turbines that deliver electric energy in synchronism with the network of the Southern California Edison Co. Solar One will be used as an experimental system for the next five years and is expected to help reduce the cost of energy from future central receiver systems which could, of course, also be used to supply high-temperature industrial process heat.

In an effort to encourage industrial process heat developments, the Department of Energy began in 1976 to devote a substantial amount of its budget to the construction of experimental field installations. These installations



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

Fig. 3 Temperature ranges attainable with different solar technologies.

encompassed many different technologies, applications, and geographic locations, e.g., a flat-plate hot water system for an industrial laundry in California, a field of parabolic troughs to provide steam for a food processing plant in Oregon, flat-plate air collectors to provide heated air for a soybean processing plant in Alabama, and evacuated tube collectors to generate steam for processing orange juice in Florida. Unfortunately, with some exceptions, the track record for these early systems has not been good. A review conducted by Dr. Edward Lumsdaine for the Florida Solar Energy Center of 16 systems in the first cycle of DOE demonstration projects calls them "uneconomic" and their performance "dismal" [7].

There are several reasons for the lack of success in these early systems. Some of the projects were not well suited for solar energy utilization. There were errors in system design due to poor end-use matching and the installed solar capacity could not be fully utilized. There were hardware failures, e.g., leaks developed, tracking mechanisms broke down, plastic glazing deteriorated, reflective surfaces peeled or deteriorated under harsh environmental conditions, and the glass enclosures of evacuated tube collectors failed due to differential expansion stresses. High parasitic losses plagued some systems, while others suffered large thermal losses from storage. System efficiencies ranged from 8 to 20 percent, about one-fourth to one-half the level of performance that had been predicted by model analysis in design and which is required for successful commercial applications.

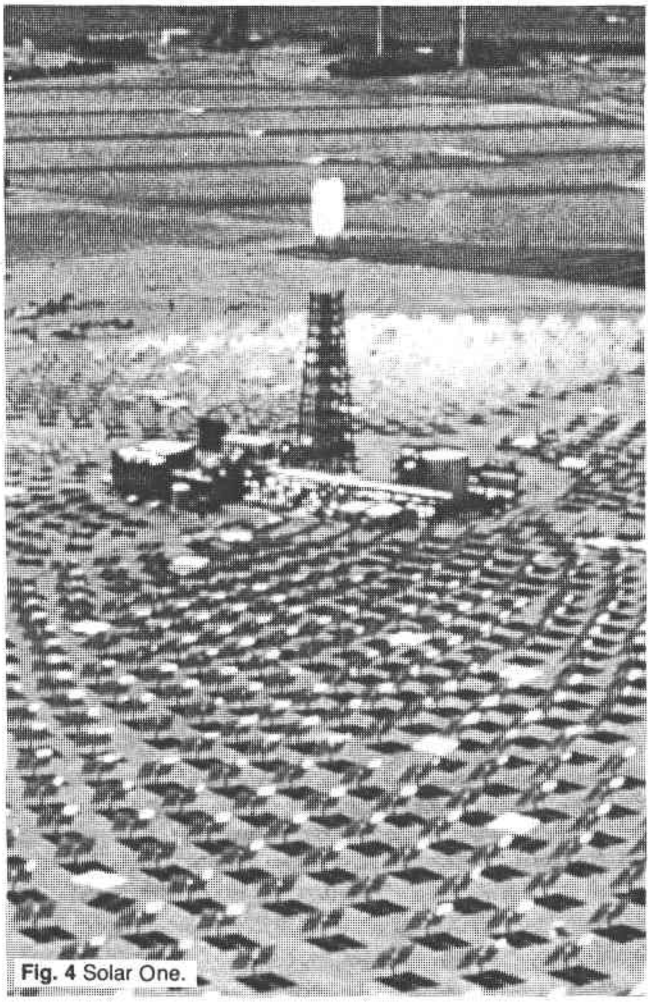


Fig. 4 Solar One.

Certainly, if these early systems are judged from the industrial perspective in terms of performance and economics, they have not been successful. In retrospect it is apparent that with better engineering design many of the problems could have been avoided. However, critics of the early DOE-supported cycles should remember that these systems were built primarily to provide a learning experience. Anyone who expects a new technology such as solar industrial process heat to be economically successful and technically viable without trial and error in the field is not familiar with the traditional development of a new technology. If the industrial process heat demonstrations are viewed as field experiments, they have been successful because they have shown us the kind of things that will work in the field and the kind of things that will not. It is obvious, however, that the DOE program has not been successful in demonstrating how to build economical systems. That should be left to industry. However, the experience gained will make it easier for the private sector to succeed.

The commitment of the current administration is to support long-term, high-risk research, whereas commercialization of solar energy is considered to be the responsibility of the private sector. Furthermore, it is expected that each solar technology should compete in the free market and be used only when it is technically ready and economically competitive. There is no question that this is a reasonable approach, but it must also be noted that the cost of fossil fuel, as well as of solar energy, depends on a number of factors which are not determined by the market alone.

The cost of delivered energy from renewable as well as nonrenewable sources depends on factors such as the capital investment, cost of maintenance, life expectancy, and efficiency of the production and conversion systems, fiscal parameters such as interest rate, discount rate, and inflation, and institutional parameters such as taxing and pricing policies. Recently less tangible factors such as the value of environmental quality and esthetics have influenced the cost of energy. But, in addition to the above, the cost of solar industrial process heat depends on the following, more specialized, parameters:

- **Technology** Cost depends on the technology used, e.g., flat-plate versus tracking parabolic troughs.
- **Load temperature** At lower temperatures, collectors operate at higher efficiencies and permit the use of lower cost installations.
- **Size** There may be some economy of scale for larger installation since fixed costs, such as the control systems or engineering design, can be spread over a larger investment.
- **Location** There are significant differences in performance with insolation. Obviously, supplying industrial process heat in a location that has high insolation will reduce cost.
- **Process** The process for which the solar industrial process heat equipment is used will create significant variations in cost. For example, a process that operates seven days per week can supply approximately 20 percent more energy per capital investment than a process that operates only five days a week.
- **Backup** Since the availability of solar energy is subject to variations due to time of day, season, and weather, the cost of delivered energy depends also on the cost, amount, and availability of backup energy required.
- **Storage** The amount of storage used, or necessary, determines the capital cost. Today, the best applications are those

that require little or no storage and are sized to deliver all of the collected energy continuously. If the cost of storing thermal energy can be reduced, the optimum storage capacity may change.

In planning a market penetration scenario for solar energy in industrial applications it is obviously of advantage to concentrate first on areas with high insolation and high cost of competing energy, processes that need only low temperatures, and industries that operate seven days a week and require little or no storage.

The most successful application of solar energy technology in the marketplace has been for domestic water heating. The thermal utilization potential of this application is similar to that of an industrial process heat system. Domestic hot water systems can use, if properly sized, essentially all the collectible solar energy at a relatively low process temperature and operate throughout the year. In Boulder (Colo.), over 50 percent of the new houses constructed have solar domestic hot water heating systems, and in Israel between 2 and 3 percent of the total national energy is supplied by solar hot water systems. In San Diego (Calif.), a law was passed a few years ago requiring that all new construction in that county must have solar domestic hot water systems. The results have been very encouraging and in the buildings monitored, more than 75 percent of the total energy needed for domestic water heating is supplied today by solar energy in that county [8].

The widespread use of solar domestic hot water systems is encouraging, but it would not have occurred if Congress had not passed a law which allowed 40 percent of the initial cost as tax credit if the system is installed by the user in his private residence. In addition to the federal tax credit, many states have adopted tax credits of their own. In California, the state with the most favorable condition for solar hot water heating, the owner needs to pay only about 35 percent of the actual installation cost [9].

The incentives for industry to install their own solar thermal systems are less favorable. In contrast to the homeowner, industry can deduct the full cost of fossil fuel from its income as an operating expense. Thus, oil priced at $30 a barrel on the market costs an industrial user in the 50-percent marginal tax bracket only half that much. If this same industry were to install a solar system, it would not only have to repay the solar investment, but it could no longer deduct the cost of the energy replaced by solar energy as operating expense [10]. Consequently, without tax incentives, the use of solar energy by industry increases the amount of taxes it must pay. Industrial solar energy use would, in the long run, actually increase the tax revenue collected by the government. This could serve as an economic justification for the government to offer tax incentives.

For example, for a properly designed and efficiently operating industrial process heat system installed in a favorable part of the country, the increase in tax revenue to the government over a period of 10 years from the reduction in tax-deductible energy used by industry, would allow a 40-percent tax credit of the initial capital cost without a net loss of revenue to the government. If the industry were to depreciate the solar equipment over five years, the tax deduction taken approximately equals the tax deduction if fossil fuel had been used. But after that time, the government would receive extra income, equal to 50 percent of the increased earnings accruing to the company from fuel savings. If a tax incentive had been the trigger for the installation of the solar equipment in the first place, the government would actually begin to recoup this investment about five to six years after installation. If the life expectancy of the equipment is 10 years, the government could recoup a 40-percent tax incentive and the user would, after five or six years, actually get energy at half the market price, as though he were using fossil fuel. This example shows that the actual cost of energy not only depends on market forces, but also on tax policies.

The government has traditionally provided subsidies for developing energy sources and this policy tends to make solar technologies today less competitive in the marketplace than they would be otherwise. The government has invested over $200 billion in financial incentives to develop coal, oil, natural gas, nuclear energy, and hydroenergy [11]. These supports have ranged from funding of research for the development of the technology to tax provisions to stimulate production. For example, over $100 billion have been expended for incentives to the oil industry. The largest incentive to the petroleum industry was the reduction of existing taxes through intangible drilling expenses, and the percentage depletion allowance—over $50 billion over the past 50 years. The second largest category of incentives included stripper well price incentives, incentives for new oil production, and subsidies for tankers and pipelines. These totaled $42 billion between 1921 and 1977.

An analysis by Bezdek and Kannan of past energy subsidy policies revealed two rationales for energy production incentives [12]: to promote a new technology during its early stages, and to pay the difference between the value of an activity to the private sector and its value to the public sector. Support of nuclear energy represents an example of the first, while the Rural Electrifica-

Investment Tax Credits in Percent of Initial Cost

Sector	Front End Levels* (Initial Year)	(Final Year)	Sustained Level to yr. 2000
Residential	35 (1980)	31 (1982)	20%
Commercial	36 (1980)	18 ( )	15%
Industrial	30 (1980)	21 (1988)	21%
Utility	40 (1980)	30 (1990)	20%

*Linear Decline from initial to final year
**Battelle Northwest, 1978

Fig. 5 Federal incentives necessary to achieve 20% solar market penetration by the year 2000.**

1 Energy Tax Credits (ETC)	15%
2 Investment Tax Credit (ITC)	10%
3 Exemption from "at risk" limitation—actual cost eligible for ITC	Increases $s allowed as ITC
4 5-year accelerated depreciation of solar equipment (Economic Recovery Tax Act of 1981)	Accelerates payback

Fig. 6 Current federal incentives for solar industrial process heat

tion Administration (REA) is an example of the second. Both presently apply to the development of solar energy.

The historical precedent of subsidies provided for conventional energy development could justify taxing policies that would accelerate the widespread industrial use of solar energy and make it economically more viable. In 1978 Battelle Northwest Institute made an analysis of federal incentives necessary to stimulate solar energy development and their results are shown in Fig. 5. According to this study, investment tax credits of approximately 40 percent for utilities, 36 for commercial applications, and 30 for industrial processes would initially be required to achieve a 20-percent market penetration in the year 2000, as projected by the Domestic Policy Review.

Current federal tax incentives for solar industrial process heat are shown in Fig. 6. With these incentives SIPH (solar industrial process heat) could be economically competitive with oil in favorable locations provided the solar systems perform at their thermal potential and all the energy from the system can be used by the process to which it is applied. This situation has encouraged private investors to finance the construction of SIPH systems and then sell the energy to industry. The sole commitment required from the industrial end-user is an agreement to purchase the system's output at a set percentage of conventional energy cost. Luz Engineering, a California-based firm, has secured financing for a half-dozen large projects, including three southern textile mills where more than 200,000 sq ft of parabolic troughs are to be installed [7].

These and similar examples indicate that solar industrial applications can be, at least from the point of view of the companies arranging for third-party financing and their investors, potentially cost-effective. However, these expectations are based on the assumption that the performance of the solar systems will meet predictions based on their thermal potential, operation and maintenance cost will not get out of hand, and the system lifetime will be sufficient to recoup the investment. Since with third-party financing all of the risks are effectively shifted from the end-user to the third-party investors, the key question becomes whether these private sector players can do a sufficiently good job in making SIPH systems efficient, cost-effective and reliable to sustain a viable market that will encourage others to follow their lead.

In the near term there are still other barriers to be overcome. Solar energy systems are at a disadvantage in achieving market penetration due to average cost pricing, price controls on some conventional energy sources, and high interest rates. President Reagan's decontrol of U.S. oil prices in 1981 represented a major step forward in making solar energy economically more attractive. But natural gas prices are not scheduled to be decontrolled until 1985. The relatively low price of natural gas will, therefore, deter the use of solar energy where gas is available. Another barrier for solar energy is the current attitude that places more emphasis on the immediate future than the mid- to long-term future. As a result, purchase decisions are usually based on first cost rather than on life cycle cost.

Ben Franklin once asked, "What has the future ever done for me?" It seems that we still have not found the answer, for existing tax incentives for solar energy are due to expire in 1985 and unless Congress renews them, solar systems may cease to be competitive, even if they can technically live up to expectations. But we are paying over $70 billion per year to import foreign oil. This is equivalent to about 3 percent of our GNP and exceeds the combined net assets of General Motors, General Electric, and Ford. Clearly, this is not a healthy state of affairs and we must work to reduce this enormous drain of foreign exchange for oil by using more of the energy sources available in this country.

The effect of energy conservation on the petroleum market is similar to the effect of using solar energy. Under normal conditions oil production is approximately equal to market needs. However, experience in the last 10 years has shown that when conservation measures are introduced they can significantly reduce the demand for petroleum. The effect of solar energy use and conservation results, then, not only in savings due to a reduction in consumption, but more important, the price of oil decreases as countries with excess production lower their price to capture a larger share of the market. Thus, continued conservation and increased production of energy from solar resources can break the stranglehold of cartels such as OPEC and could be an effective means of fighting inflation that has been fueled by continued increases in energy costs.

We have so far attempted to justify the development of solar industrial process heat technology for its economic benefits. However, solar energy possesses significant external values whose benefit to society may outweigh the economic benefits to individual users. Solar energy systems, once installed, create little or no environmental pollution; increased utilization of solar energy enhances our national security by making the country less dependent on foreign oil and thereby gives the U.S. greater flexibility in conducting its foreign policy; finally, the increased availability of solar energy technologies decreases the risk of nuclear proliferation.

During the past election, several referendums favoring a nuclear freeze have been on the ballots in many parts of the country, and almost all of them were approved [13]. This suggests a growing fear that the increased availability of nuclear weapons could trigger a nuclear war, and national leaders have repeatedly expressed concern about the possible use of nuclear power plants to produce plutonium for nuclear weapons. Current efforts toward preventing nuclear proliferation will have more consistency and credibility if we could provide viable alternatives to nuclear power. The development of solar energy in this country would demonstrate that we are concerned about nuclear proliferation and could be a significant step toward arresting the availability of nuclear fuels worldwide.

It is a proper and generally accepted role of government to provide for the best long-term interests of the nation. Since it is generally agreed that within the next 10 to 20 years this country could experience shortages of fossil fuels, it would be prudent for the government to develop promising alternatives, including solar energy. A viable solar energy industry in the overall energy infrastructure would strengthen the economic and political posture of the United States. But the lead time required to develop a new energy technology, as evidenced by the development of commercial nuclear power, is somewhere between 25 and 50 years, even if ample government subsidy is provided [14]. This suggests the need to support development of solar energy now, if it is to be available when needed in the future. A viable infrastructure of solar manufacturers, distributors, users, and research establishments could protect the U.S. against many uncertainties during the rest of the century and beyond. If it should turn out that fossil fuels are more abundant than current estimates indicate, the loss to our society would be less important than the consequences to this country if renewable energy development is not undertaken in a timely manner and a fossil-fuel shortage would impose a sudden curtailment on industrial activities.

But even if the Middle East should not experience any new political problems, the economic effects resulting from the outflow of petrodollars are detrimental to the welfare of this country. Many of the oil exporting countries allocate large sums of money to purchase modern military equipment, and much of it is bought from the U.S. This creates a shift in the domestic production system from productive, nondefense-related industrial and agricultural sectors to less productive defense industries [15]. Such a shift is detrimental to full employment [16], and given the large unemployment in this country at the present time, all measures, such as building renewable energy systems, that can provide for continued long-term employment stability, are in the best interests of this nation.

What is the answer to the question "Can industry afford solar energy?" In the long run there is no doubt that solar energy can and will be used by industry. But for the short run, the outlook is uncertain. However, SIPH could begin to penetrate the market as soon as the following conditions are met:

1 Solar technology is proven in the field.

2 Solar systems are integrated with the processes they serve to achieve maximum yearly efficiency.

3 Lifetime of at least 10 years is assured for solar equipment.

4 Sufficient economic incentives for solar energy are available.

5 Adequate financing capital is available.

6 Performance guarantees can be given to investors.

The first three of these items are challenges to engineers. The fourth and fifth are institutional and political challenges. The last is a challenge to industry and the professional societies responsible for codes and standardized development.

The economic and social costs of shifting to a new energy supply system will be large and the transition will take time. But an industrialized nation runs on energy and cannot afford to run out. We must, therefore, plan our energy future to ensure a continued supply for industry, which is the biggest energy consumer. The above challenges for industrial use of solar energy are formidable, but they are not impossible to meet. For the sake of the future stability and the economic health of our country, a concerted effort should be made to meet the challenges of developing solar technologies, along with coal and nuclear power, so we can count on all of our indigenous energy resources when we need them.

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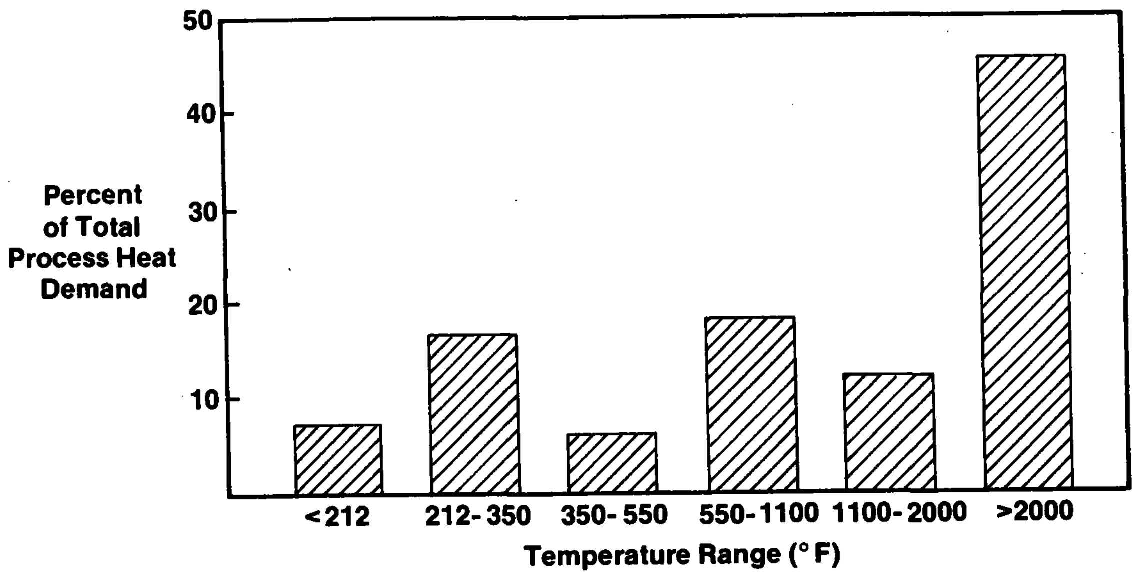
SECTION 2.0

SOLAR TECHNOLOGY FOR PROCESS HEAT

The efficiency of solar thermal collectors depends to a large extent on the temperatures of heat output required. Industrial process heat (referred to here as IPH) accounts for approximately half of manufacturing energy end-use demand and is required over a wide range of output temperatures, as shown in Fig. 1 (InterTechnology 1977). Therefore, although a large variety of solar thermal technologies are theoretically suitable for IPH, only certain technologies offer conversion efficiencies high enough to be commercially viable. Many of these collector technologies have been field-tested in residential, commercial, or industrial settings; others are still under development in laboratories throughout the United States. As noted in Fig. 2, the practical ranges of operating temperatures have considerable overlap. The choice of a particular solar collector and heat transfer system from these overlapping operating ranges depends on local climatic conditions, process requirements, and of course, cost.*

Figure 1. Distribution of Industrial Process Heat Demand by Temperature Range (1974)



Source: InterTechnology, 1977.

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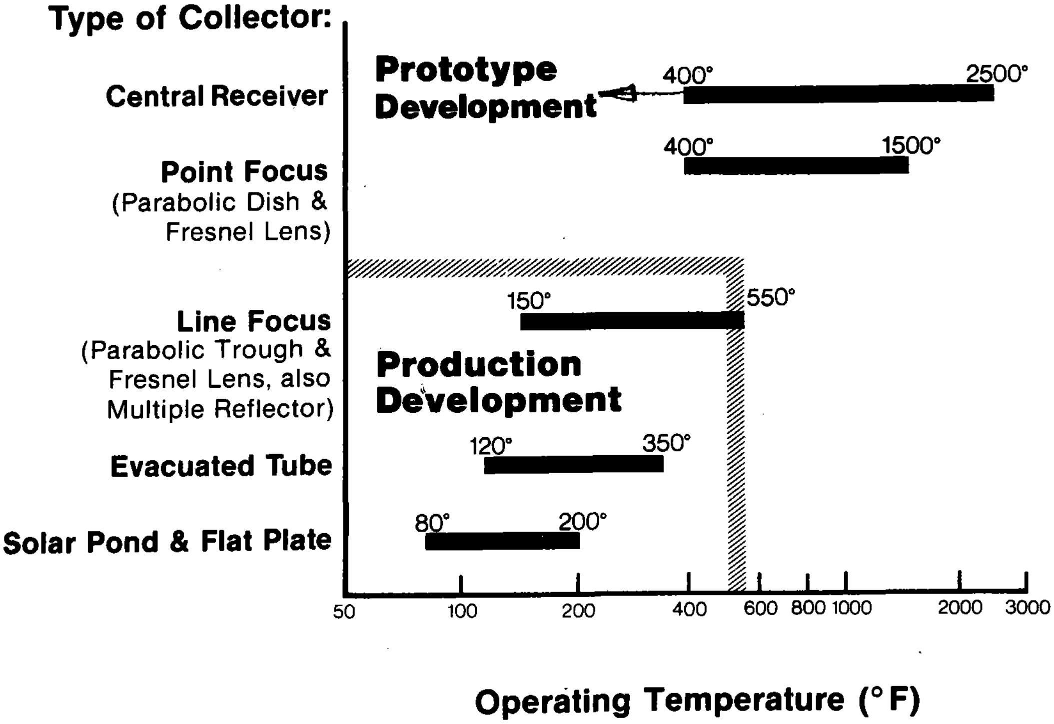
*A computerized routine for comparison and selection of appropriate solar collectors and heat transfer systems on the basis of these conditions has been developed at the Solar Energy Research Institute (SERI). The computer program is known as PROSYS/ECONMAT and is described in SERI/TR-34-091, End-Use Matching for Solar Industrial Process Heat.

Figure 2. Practical Operating Temperature Ranges of Several Types of Solar Thermal Collectors for Industrial Process Heat



Collector technologies may be conveniently divided into four categories, based on optical characteristics. Nontracking, nonconcentrating collectors (almost exclusively comprised of the so-called flat-plate collector) have the broadest base of installation and development history. Over 80,000 active solar heating, cooling, or hot water systems have been installed in residential or commercial facilities across the U.S., and most rely on flat-plate solar collectors. Nearly 50,000 sq. ft. of flat-plate collectors have been installed at six sites for industrial applications. In all, nearly 12 million sq. ft. of medium temperature collectors have been shipped by domestic producers since 1974 (Bureau of the Census 1980).* Nontracking, semiconcentrating technology is typified by the evacuated tube collector in connection with either cusp or V-trough reflector backings. These collectors appear to be gaining more favor among plant engineers for their ability to obtain output temperatures higher than the traditional flat-plate collector (up to 350°F) while maintaining the simplicity of a fixed mounting. The third major category is the line-focusing, tracking collector. Several variations of line-focusing technology have been proposed; nearly all are capable of extended operation at output temperatures of approximately 500°F. The parabolic trough collector, in which optical concentration ratios of

*Despite the volume of this production, there are still significant engineering problems to be overcome in flat-plate collector installations. See, for example, remarks by HUD official Joseph Sherman in the Solar Energy Intelligence Report, Vol. 6, No. 8, 25 February 1980, p. 71.

50 or more can be obtained, is the most commonly used device. Over 39,000 sq. ft. of parabolic trough collectors have been installed for industrial use since 1977.

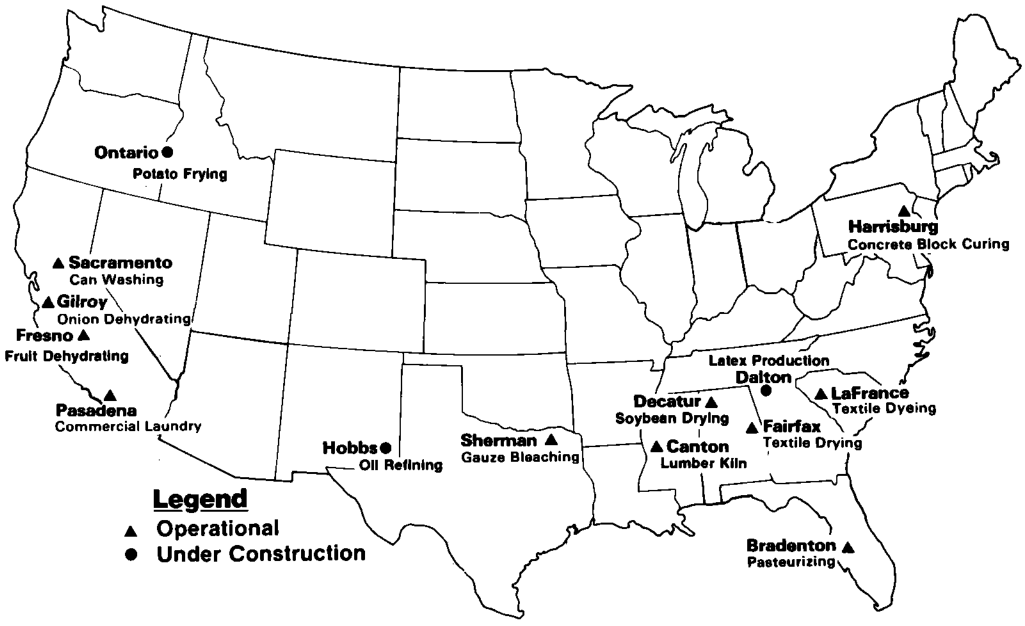
Laboratory and pilot development of tracking, point-focusing collector technology is bringing these technologies to the verge of industrial deployment. Two major categories of point-focusing technology have been developed: (1) the distributed parabolic dish and (2) the central receiver. These collector technologies, because of their ability to provide concentration ratios of up to 1000, are able to produce temperatures in excess of 2500°F.

The solar collector array acts as a heat source for energy delivery systems tailored to particular process needs. For example, by circulating heat transfer fluids through the collector array (including ethylene glycol/water solutions at low temperatures or commercial heat transfer oils at higher temperatures), industrial hot water, hot air, or industrial steam may be provided via heat exchangers. Occasionally, it may be appropriate to substitute oil heated directly in the array for heat transfer oils heated in process furnaces. Alternatively, water or air may be heated directly in certain types of solar collector arrays and used in the process. Although these "direct" systems offer the highest possible efficiencies, they are often impossible to implement because of the standards of purity of the industry in question (e.g., food processing) or because of inherent difficulties with freezing and storage. Steam may also be produced directly in solar collector arrays by flashing water to steam or by direct boiling (as in central receiver technology).

Nearly every system and collector concept is represented in the Department of Energy's field engineering test program. Rather than pursue an exhaustive theoretical discussion of these concepts, this paper concentrates on a discussion of the particular system concepts and applications contained in the federal program.

The Department of Energy has sponsored the design, and in some cases construction and operation, of 18 solar industrial process heat projects since 1975 (see Fig. 3). Eleven of

Figure 3. DOE Solar Thermal IPH Field Experiments



these projects are now operating; six have been operating for at least one year. Three more projects to provide solar-generated process steam are under construction and will be operational in 1981. In addition, conceptual designs have been initiated for other large-scale steam systems and soon will be begun for several large-scale hot water systems. These field projects represent the state of the art in collector equipment and in system design. It is instructive to review their status as an indicator of present trends.

SECTION 3.0

REVIEW OF COST AND PERFORMANCE OF SOLAR IPH SYSTEMS

By and large, solar IPH systems will supplement existing heating systems by displacing fossil fuels. Although energy storage has been incorporated into several of the current demonstration systems, each retains a full-capacity fossil fuel backup. As a result, the success of solar IPH systems is measured by annual fuel savings, which are directly proportional to the energy delivery capacity and utilization of the solar system. The energy delivery capacity of solar IPH systems designed in the DOE program vary from a predicted high of 370,000 Btu/year per square foot of collector aperture area to a low of 110,000 Btu/yr (see Table 1). This predicted delivered energy capacity is based on 100% utilization of the solar system; that is, solar heat from the collector array was assumed to be usefully absorbed by the process at all times that the system was operating. Actual experience with the operating demonstrations shows that full utilization is infrequent. This lack of utilization, along with unexpected inefficiencies in the delivery system and in the collector array, led to lower annual outputs than predicted in design. As shown in Table 1, the actual annual energy capacity varied from a high of 148,000 Btu/yr per square foot to a low of 35,000 Btu/yr per square foot for the five systems for which operating data is available.

Because the energy delivery of a solar thermal IPH system is calculated with respect to actual delivered heat at the point of use, a solar system providing one Btu of energy actually displaces more than one Btu of fuel equivalent. The efficiency of conversion of the solar system is implicitly contained in the energy delivery figures given; the efficiency of fuel conversion (which may vary from 65% to 85% in conventional boilers and furnaces) is often not included in calculating fossil energy displacement. The fuel savings of a solar system, then, are equal to the annual energy capacity of the system divided by the conventional fossil fuel conversion efficiency.

The costs of solar IPH systems have varied considerably with respect to location, collector type, and auxiliary system construction requirements. Design costs of IPH systems are shown in Table 1, along with actual costs incurred in six completed projects. Although capital costs in terms of dollars per square foot are commonly quoted, these units can be somewhat misleading. To show costs that are related to units of energy capacity, the capital costs of the systems are also shown in dollars per million Btu per year of nominal output. [This unit, similar to cost units of $/kW, or $/(MBtu/h), is adopted for convenience in calculating levelized solar costs and for consistency with normal conventional practices; throughout the paper the unit will be referred to as energy capacity cost and written as $/(MBtu/yr)]. Note that the costs vary from a low of 108 $/(MBtu/yr) to a high of 536 $/(MBtu/yr) on a predicted performance basis. The average cost, exclusive of the highest and lowest costs given, is 276 $/(MBtu/yr). Assuming that simple, after-tax payback periods of three to five years will be required of energy saving investments, one finds that the break-even market price of the displaced fuel would have to be between $94 and $52 per million Btu to justify a solar investment at this average cost.*

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*Break-even fuel costs have been calculated on the basis of a simple (undiscounted) payback formula that takes into account tax effects (see Dickinson 1979, p. 25). Straight line depreciation over 10 years was assumed, annual operating and maintenance costs were taken as 3% of initial capital cost, an investment tax credit of 20% was used, an effective total tax rate of 50% taken, and displacement of fuel used at 70% efficiency was

Table 1. COST AND PERFORMANCE OF SOLAR THERMAL IPH SYSTEMS

		Annual Energy Delivery				Actual Net System Efficiency	Capital Cost		
		Predicted		Actual			Predicted		Actual
System	Approximate Size (ft^2)	(MBtu/yr)	(Btu/yr)/ft^2	MBtu/yr	(Btu/yr)/ft^2	%	\$/ft^2	\$/(MBtu/yr)	\$/(MBtu/yr)
1	7,300	2,156	290,000	—	—	—	74.80	253	—
2	6,700	1,400	210,000	369	55,000	8.1	85.10	407	1,541
3	9,200	1,500	160,000	320	35,000	9.1	42.80	263	1,233
4	13,100	3,700	280,000	744	57,000	19.1	56.00	198	986
5	2,500	900	360,000	370	148,000	32.5	87.10	242	593
6	21,000	2,300	110,000	1,135	54,000	17.5	24.60	225	456
7	8,300	1,219	150,000	—	—	—	51.13	348	—
8	11,500	1,400	120,000	—	—	—	65.00	536	—
9	10,000	2,700	270,000	—	—	—	74.00	274	—
10	6,500	1,600	250,000	—	—	—	70.00	284	—
11	20,200	2,550	130,000	—	—	—	55.00	438	—
12	9,500	2,900	300,000	—	—	—	68.00	222	—
13	10,600	3,900	370,000	—	—	—	40.00	108	—
14	15,400	5,000	320,000	—	—	—	50.00	156	—

Source: Kutscher and Davenport (1980) and internal records.

Even with a ten-year payback allowed, the break-even cost would be $20/MBtu, or nearly $120 per barrel of oil. Obviously, at such costs, solar IPH systems are not competitive.

More recent cost projections have been made for proposed solar industrial process heat systems that have an average predicted capacity cost somewhat less than 276 $/(MBtu/yr). Proposed solar industrial process heat projects, including cost information where available, are shown in Table 2. The average capacity cost for these proposed projects is about 160 $/(MBtu/yr). Break-even fuel costs would vary between $54/MBtu (or about $325/bbl of oil equivalent) for 3-year payback to $12/MBtu (or about $72/bbl of oil) for a 10-year payback. If a 10-year payback were acceptable, then it is possible that certain companies paying for fuel purchased at or near marginal world oil prices (currently around $42/bbl) would find solar supplement to process heat an acceptable investment.

Unfortunately, the poor performance of the field experiments described in Table 1 actually diminishes the prospects of economic competitiveness in the near term. When actual operating annual output is folded into the calculation of capital cost for capacity, the average cost is 962 $/(MBtu/yr). Hence, the break-even equivalent oil cost is over three times higher, or approximately $460 per barrel. Two conclusions are obvious: first, actual obtained performance of solar IPH systems must improve dramatically; and second, installed costs must be reduced in a commensurate fashion. Durability and reliability require far more demonstration, of course, but it is clear that without significant general improvement in cost effectiveness, solar IPH will hardly offer an attractive opportunity for industrial capital. The remainder of this paper describes the actions that are being taken, or must be taken, in order to make solar IPH a viable investment.

Table 2. PREDICTED COST AND PERFORMANCE OF PROPOSED SOLAR THERMAL IPH SYSTEMS

System	Approximate Size (ft^2)	Annual Energy Delivery (MBtu/yr)	Capital Cost $/(MBtu/yr)
1		20,000	147
2	≤50,000 (systems 2–7)	9,000	219
3		24,000	100
4		12,600	209
5		14,700	152
6		8,760	155
7		17,500	144
8	237,900	118,700	-
9	171,300	70,400	-
10	671,000	339,000	-
11	210,000	179,200	-

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SECTION 4.0

PROSPECTS FOR SOLAR IPH

Successful implementation of solar thermal systems in industry will depend upon an attack on at least three fronts. First, the cost and performance of solar thermal systems for IPH must be improved substantially. Second, the most appropriate and advantageous applications for this technology must be located and developed. And third, the government, if it decides involvement is warranted, should act to encourage implementation through the various instruments of policy at its disposal. The successful introduction of a new technology into the industrial marketplace must follow those attacks in sequence. In other words, primary emphasis must be placed on obtaining a viable technology. Government incentives or market development can make no headway without a viable product.

To obtain the cost and performance improvements necessary to promote solar technology as a viable investment, it is first important to establish exactly what performance and cost improvements are required to be cost-competitive: cost and performance goals must be established. There are obvious physical limitations to performance improvement; the efficiency of a solar thermal system cannot exceed 100%. What average annual efficiency can ultimately be obtained is the subject of a great deal of research at the present time. According to scientists at the Solar Energy Research Institute, physical limitations of the properties of reflective materials, glass, heat transfer media, and insulation will probably limit solar system average annual efficiency at intermediate temperatures to approximately 60%. This 60% limit should be considered as an ultimate goal, approachable only with extremely precise control, high-quality materials, and efficient system design and operation. Cost limits for the solar thermal systems are more difficult to define, except that, of course, the cost of the system may not be zero. A possible lower limit on the cost of solar systems, based on basic materials and land costs, is $\$10/ft^2$.

The combination of cost and performance is embodied in the energy capacity cost of solar IPH systems, expressed as \$/(MBtu/yr). Assuming that at least a 3-year payback will be required of energy-related investments in the future,* and that alternative fuels will be available at or below the current marginal cost of crude oil, the appropriate solar cost/performance goal may be calculated. Hence, for an alternative fuel price of \$7/MBtu and a fossil fuel conversion efficiency of 70%, solar thermal IPH systems must not exceed an energy capacity cost of 20.62 \$/(MBtu/yr). If the best possible solar system efficiency were obtained and the best possible location was available (for example, El Paso, Texas) the annual delivered energy would be $0.60 \times 840{,}000\ (Btu/ft^2)/yr = 504{,}000\ (Btu/ft^2)/yr$. In order to meet a goal of 20.62 \$/(MBtu/yr), the system would have to be installed at less than \$10.40 per square foot of collector aperture area. Considering that the average cost of installed systems in Table 1 is about $\$61/ft^2$, the challenge represented by this goal is significant.

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*In interviews conducted by consultants for the Southern California Gas Company during 1977, it was found that a number of companies were willing to consider 5-year payback periods on energy-related investments. If a 5-year payback is assumed in the above calculations, the required installed system cost must be no greater than about \$19.00 per square foot.

In addition to the obvious need for system cost reduction and better output performance, solar thermal technology is in need of improved durability and reliability. In many cases, simple improvements in engineering practice will result in better IPH systems. In others, more basic collector or component improvements are needed.

Since one is faced with such distant prospects of widespread cost-competiveness of solar process heat, any near-term implementation of this technology is crucially dependent on the choice of application. Not every industrial concern has the same outlook for fossil fuel availability or price. In certain situations, the actual cost of fuel may be much higher or much lower than the $7/MBtu assumed above. In addition, some industrial processes are more physically compatible with solar thermal heat (and the way in which it may be supplied) than others. Recent investigations at the Solar Energy Research Institute indicate that solar energy is most suited to applications which have most, or all, of the following properties:

(1) a location with high solar insolation and high ambient temperatures,

(2) a location with low air pollution levels so as not to degrade collector surfaces,

(3) a location where environmental standards or fuel regulation discourage or prohibit fossil fuel use,

(4) low temperature requirements in the process,

(5) continuous operations where temperature or heat rate control are not critical,

(6) built-in storage in the process,

(7) high and rapidly escalating fuel costs or inefficient fuel usage,

(8) uncertain fuel supplies and energy-intensive or -dependent processing, and

(9) available land or roof area and suitable plant layout to facilitate the addition of a solar system.

It is likely that the coincidence of all of these factors will be found only in a few isolated industrial plants. Certain industries, such as the food processing industry, seem to possess many of these important characteristics and may be the most likely initial markets for solar energy. However, specific processes and plant locations must be identified before the applicability of solar energy can be determined. The task is nearly impossible for solar equipment suppliers to complete; as a result, the identification of specific applications will depend to a great extent upon self-evaluation by plant engineers and managers. The ability of plant personnel to recognize good solar applications will, in turn, depend upon effective communication between solar research and development programs and the industrial community regarding the status and prospects for solar IPH.

SECTION 5.0

FEDERAL POLICY AND THE PROSPECTS FOR SOLAR IPH

As stated earlier, it is important to recognize that government tax incentive and market development programs are ineffective without a viable technology base. Therefore, federal market stimulation is a final and indirect phase of government involvement and must be carefully scrutinized to ensure that such "benevolent" interference is efficient and productive. Perhaps the measure of that effectiveness should be the speed with which the government is able to withdraw from participation.

President Carter, on 20 June 1979, declared that 20% of domestic energy demand would be supplied by renewable resources in the year 2000, and that of that goal, 14% of the renewable energy (or 2.6 quads) would be provided in the industrial and agricultural sector by solar thermal energy. At predicted output efficiencies, this goal would require the cumulative installation of somewhere between eight and ten billion square feet of solar collectors in industry, equivalent to a total capital expenditure of nearly $400 billion. This goal is an ambitious one and undoubtedly will require a vigorous economic incentive program.

Federal economic incentives are most frequently associated with provisions for tax relief, since these are most often the most direct and unobtrusive means of conferring economic value upon selected classes of capital investment. Since 30 September 1978, an investment tax credit of 10% has been available (in addition to the standard 10% capital equipment tax credit) for solar process heat equipment purchased by industry. Legislation sponsored by Senator Robert Packwood (Oregon) and Representative Wyche Fowler (Georgia) in 1979, sought to increase this additional tax credit to 40%, thus making the total credit 50% for solar IPH investments. The final version of this proposal, agreed upon by a House-Senate conference committee on 11 February 1980, grants an additional 15% investment tax credit, for a total credit of 25% on solar systems purchased for industrial process heat. Three-year carryback and seven-year carryforward of the credit would be allowed* (SEIR 1980). As shown in Fig. 4, the effect of a 25% investment tax credit rather than the current 20% credit is so small as to be ineffective. The effect of a possible 50% investment tax credit is enough, however, to make solar IPH systems installed for 160 $/(MBtu/yr) a competitive investment with ten-year payback where displaced fuel costs an average of $5/MBtu.

The other major instrument of tax policy at the federal government's disposal is the definition and establishment of allowed depreciation, or tax, life. Currently, the minimum allowed depreciation period for capital equipment (in order to recover the full value of investment tax credits) is 7 years. Ordinarily, plant energy-related equipment (such as boilers and furnaces) have been allowed a depreciation life of between 15 and 23 years. In the previous calculations, a depreciation period of 10 years was assumed, because no specific rulings on solar IPH equipment have been made by the Internal Revenue Service and a shorter tax life is advantageous to capital-intensive investments. The effect of a decision by the government to allow a three-year (H.R. 5084), five-year, or seven-year amortization of solar investments is shown in Fig. 5.

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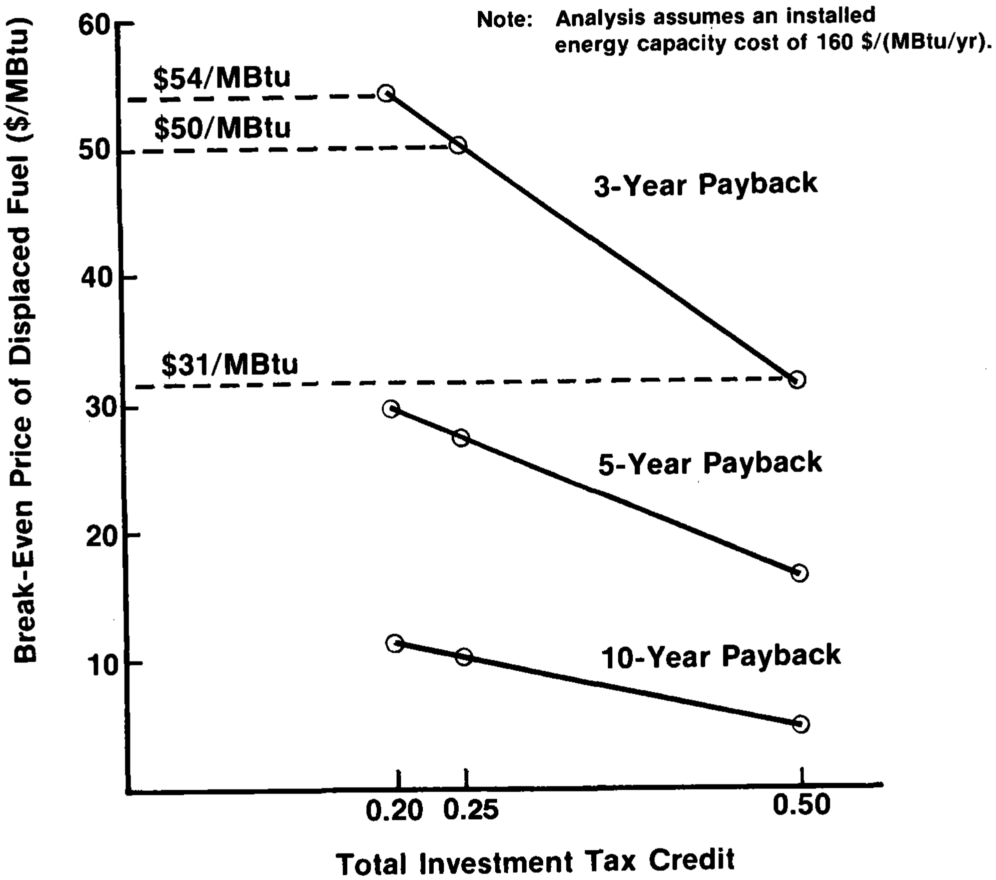
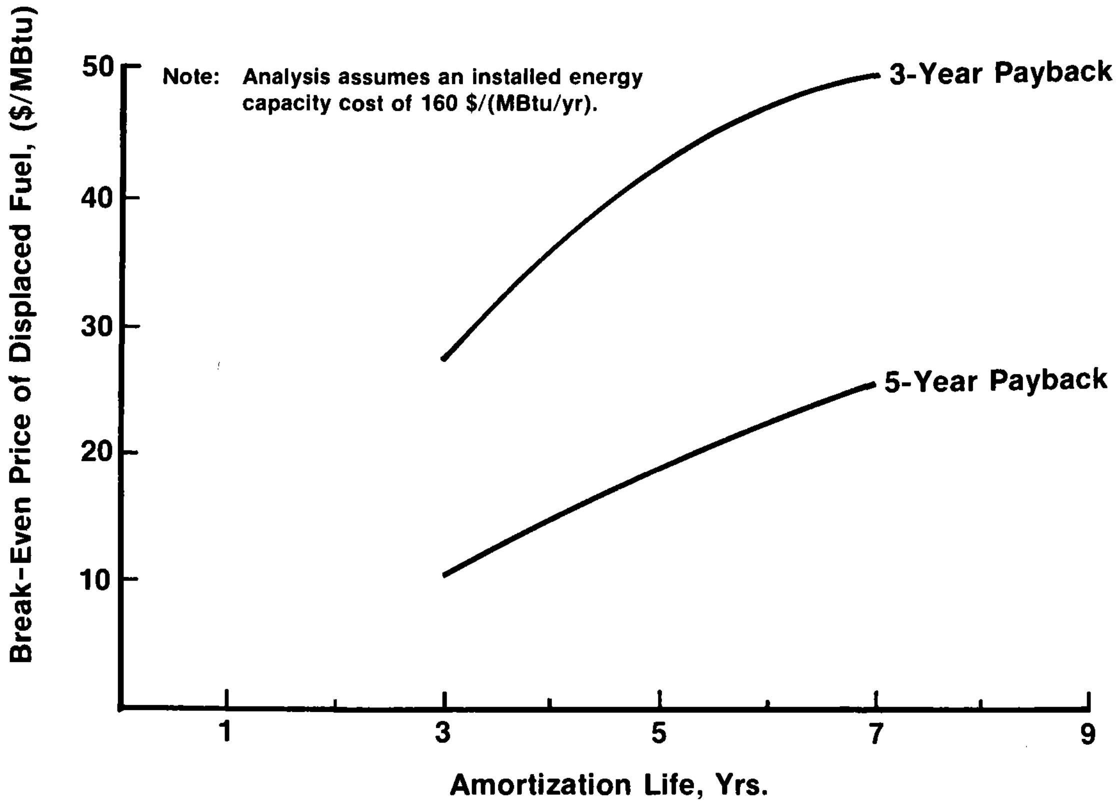
*The solar tax incentive bill (H. R. 3919) was tied to the so-called "Windfall Profits Tax" bill and is to be funded through the expected revenues accruing from petroleum excise taxes.

Figure 4. Effect of Investment Tax Credit on the Break-Even Price of Displaced Fossil Fuel



Despite the significant effects that massive federal tax incentives have on the break-even prices of competing fuel for solar IPH, it is clear that investment will be limited by two major constraints. First, as mentioned before, solar IPH technology must demonstrate reliability and functional success over a suitable period of time and be adequately matched in physical capabilities to the task at hand. Second, industry must be able and willing to commit the capital required for the purchase of such systems. Manufacturing industries spent $109.4 billion on gross capital investment in 1978 (Industry and Trade Administration 1980). Energy-related investment rarely exceeds 25% of the total annual capital expenditure of industry in a given year, so that, at most, about $25 billion was spent on energy equipment in 1978. If only 1% of the energy consumed by the manufacturing sector for process heat in 1978 (approximately 0.1 quad) were provided by solar energy in that year, the capital investment required would have been at least $15 billion [assuming solar could be installed at the optimistic cost of 150 $/(MBtu/yr)]. That is, to supplant 1% of the process energy use of industry, an investment of at least 60% of the actual planned total energy-related expenditure in that year would have been required. This severe capital strain suggests two concerns. First, the commitment of large amounts of capital to renewable energy equipment will depend

Figure 5. Effect of Amortization Life on the Break-Even Price of Displaced Fossil Fuel



heavily upon the relative importance of energy as a factor in production for the industry concerned. For example, the likelihood of significant solar investment by apparel manufacturers (SIC 23), where energy cost is only 0.7% of the value of shipments, is not large. The likelihood of such an investment by organic fiber manufacturers (SIC 2824), where energy costs are 24.5% of the value of shipments, is much greater. A second concern, even for industries facing high energy costs, is simply the availability of desired capital. It is in this area that the federal government, through the indirect support of capital formation in the financial network or through financing guarantees or federal loan banks, may have some effect.

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SECTION 6.0

CONCLUSIONS

Government policies can have a significant impact on the calculated economics of solar investments. However, tax benefits are never a substitute for reliable and efficient system performance. It is clear that although solar thermal systems for industry exhibit significant fuel savings potential and might contribute significantly to national goals of energy self-sufficiency, the current state of solar thermal technology leaves most of this potential unrealized. More experience must be gained with operating systems in industrial environments and advances in technology must be sought in order to improve both cost and performance. Industry's bottom line is profit, and profit depends on successful operation at minimum cost. Solar energy must prove itself against these criteria. If proven, the important intangible benefits of improved industrial energy efficiency and enhanced national energy security will provide a more suitable and stable business climate for United States industry.

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SECTION 7.0

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16. Abstract (Limit: 200 words)

The role of solar energy in supplying heat and hot water to residential and commercial buildings is familiar to many of us. On the other hand, the role that solar energy may play in displacing imported energy supplies in the industrial and utility sectors often goes unrecognized. The versatility of solar technology lends itself well to applications in industry; particularly to the supplemental supply of process heat of all kinds.

The realization of that potential will depend, however, on the identification of the most suitable applications and locations for industrial solar energy and the continued improvement in cost, durability, and reliability of solar equipment. The status of solar thermal technology for industrial process heat applications is surveyed in this paper, including a description of current costs and operating histories. Because the current status is unsatisfactory in view of the goals established by President Carter for solar industrial energy, this paper outlines the most important objectives to be met in improving system performance, reducing cost, and identifying markets for solar IPH. The effect of government tax policy will be of little impact until technical efficiency and cost effectiveness are significantly improved.

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