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END-USE MATCHING OF SOLAR ENERGY SYSTEMS

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END-USE MATCHING OF SOLAR ENERGY SYSTEMS

F. Kreith*, D. Kearney*,
and A. Bejan**

ABSTRACT The choice among available energy sources for a given task requires technical and economic tradeoffs on the part of the individual investor. From the national perspective, however, the effectiveness with which available energy sources are utilized may well become an overriding consideration. End-use matching is a procedure for introducing solar energy into the national energy infrastructure. The result of end-use matching is an identification of the most cost-effective combination of process energy needs, solar collector technology, geographic location, and economics by matching currently available solar system hardware with particular industrial processes and their locations. End-use matching is not intended to be a design tool for a specific plant, but rather a planning tool for determining where and for what general applications solar systems appear economically viable in the near- to immediate-term. This paper discusses the end-use matching methodology and illustrates first and second law thermodynamics analyses applied to a solar system producing process steam.

Introduction

On June 20, President Carter declared that by the year 2000, 20% of all the energy used in the United States would be derived from the sun. Clearly, an undertaking of this magnitude requires careful planning. The end-use matching process described below is designed to introduce solar energy into the overall energy infrastructure of the United States at minimum cost and maximum efficiency. Although the process is generally applicable, in this article its methodology will be illustrated by process heat applications which are well suited to near-term solar technology. Moreover, in order to meet President Carter's objective, it has been estimated that somewhere between two and three quads of energy (1 quad = 10^{15} Btu) will have to be delivered by solar collection systems for industrial process heat applications. This undertaking could cost of the order of 50 billion dollars per year, employing about a million people, and requiring a total capital investment of the order of 1 trillion dollars between now and the end of the century.(1)

Below are two widely held points of view towards solar energy:

(a) Solar energy is a clean, free, safe and inexhaustible energy source, which can be effectively utilized to solve the energy problem and provide a basis for a future lifestyle in harmony with our natural environment.

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(b) Solar energy will be of little value in meeting our energy needs because it is expensive, undependable, and useful only in warm, sunny climates. It is more of a romantic dream of those who wish to return to a more primitive existence.

Clearly, to arrive at such diametrically opposed opinions means that either people have different philosophical points of view, or they start from a totally different data base. To understand why solar energy can evoke such differences in opinion regarding its future, we must first explore in more detail the manner in which the United States utilizes its energy (Figure 1). Examination of Figure 1 shows that approximately 40% of all the energy use in the United States is for industrial purposes. A large part of this energy is used directly as heat. In order to assess the potential of solar energy in meeting the large industrial process heat demand , we must examine not only the quantity but also the quality of the energy requirement. This is shown in Figure 2, where the amount of energy in percent is plotted as a function of temperature for the industrial process heat sector. It is apparent that 28% of the total industrial energy use in the United States is heat below a temperature of 550°F. This temperature range is accessible to current solar equipment in many parts of the country. Figure 3 is a picture of a typical flat plate collector which is used to provide temperatures between 120 and 170°F. Figure 4 shows the first law efficiency of such a collector. As shown in more detail in Reference 2, the first law efficiency is defined as the useful energy delivered divided by the insolation. It is a straight-line function of the temperature difference between the collector and the environment divided by the insolation. The slope of the curve is a direct indication of the quality of the collector. The steeper the slope, the more difficult it is to achieve higher temperatures at good efficiency and the lower the maximum or stagnation temperature below which the collector can deliver useful energies. To improve the collector efficiency, it is necessary to reduce the parasitic heat losses. One such method is to surround the tube carrying the working fluid by an evacuated jacket. Figure 5 shows a collector of this sort, called an evacuated tube collector.

Figure 6 shows efficiency curves for various types of flat plate collectors which do not track the sun. However, as shown in Figure 7, the motion of the sun and its apparent location in the sky varies with time of day and time of year. Consequently, a larger percentage of solar energy is utilizable if the aperture of the collector follows the sun. This is illustrated in Figure 8, where the amount of retrievable energy for a dual-axis tracking collector, a single-axis tracking collector, and a stationary collector, using direct beam and diffuse radiation, is shown as a function of time of day.

However, the increase in availability of solar energy in a given location is not free because the cost of constructing a dual-axis tracking collector is much higher than that of constructing a single-axis or stationary tracking collector. Since economics is of concern, one should examine not only the amount of energy received, but also the capital cost necessary to install a collector to deliver a certain amount of heat per year or during its lifetime.

To achieve higher temperatures in a collector, it is either necessary to decrease the heat transfer coefficient or to decrease the area from which heat is lost. A decrease in the heat loss area can be achieved by concentration. A typical design of a single-axis tracking concentrator capable of delivering a working fluid at 550°F is shown in Figure 9. Figure 10 shows the efficiency of such a collector as a function of the temperature difference divided by the insolation. The losses from a collector of this type are shown in Figure 11, together with a sketch of the collector. The annualized performance of a typical line-focusing collector system shown in Figure 12 indicates that such a system can achieve an average efficiency of about 40% throughout the year. Figure 13 shows an entire heat exchange system typical for a process steam application.

Figure 14 shows the efficiencies and cost goals which the Department of Energy hopes to achieve in 1978, 1985, and 2000 for installed industrial process heat collector systems. It should be recognized that the collector is only a part of the total cost of an entire system. A cost breakdown for an entire system is shown in Figure 15, where the main component costs are illustrated. It should be noted that collectors account for about 75% of the cost; storage and control for about 7%, and piping installation for about 16%.

End-Use Matching

To ascertain what type of collector is best suited for a given task, it is necessary to perform an end-use matching analysis. The methodology of this analysis is shown schematically in Figure 16. To perform end-use matching, it is necessary to know the quantity of heat as well as the temperature level at which it must be supplied; in addition, one must have information on the generic solar collector technology in the form of first law efficiency data versus temperature difference for the insolation in question. Finally, one must know the weather pattern, in particular the amount and temporal distribution of direct and diffuse radiation. With this information, it is possible to predict the amount of energy that can be delivered by a solar system at a given temperature level.

In addition to the technical performance, one must also ascertain the cost of the total solar energy delivery system, as well as the price of the competing energy source. From that information, it is possible to calculate the value of the solar system for given economic parameters, such as term and interest rate of loan, expected inflation rates, etc. The values chosen will depend on the judgment of the person making the calculations.

The connecting link between the energy analysis presented so far, and the total societal input required to deliver this energy, can be attained by an analysis from Ref. 3. In a remarkably simple and straightforward manner, Krenz showed (3) that the amount of energy required to produce a dollar's worth of service for capital equipment is remarkably stable across the entire economy. Excepting motor vehicle equipment and drugs and toilet preparations, the energy required to produce a dollar value of goods or service is approximately 1 watt-year (see Figure 17). Thus, an analysis based upon an economic optimization is for all practical purposes the same as an analysis based upon energy considerations, provided one is dealing with a mature industry. Although solar can by no means be considered a mature industry at this point, it can be surmised that if the actual national solar goals are to be met, the production of solar collectors will have to become a significant part of our industrial capacity.

Figure 18 shows the distribution of industrial heat requirements in the shaded areas as well as the insolation level in the United States. It can be seen that there are a number of regions where industrial heat requirements exist and the insolation levels are also high. Thus, in those areas, installation of solar equipment will yield the largest energy replacement of fossil fuels at minimum cost and should, therefore, be pursued first. However, once the IPH needs of a given area and given temperature region which looks particularly promising have been satisfied, solar energy will have to be used for economically less advantageous tasks or in regions with lower insolation.

In order to assess the potential of solar energy on the basis of the second law of thermodynamics, it will be assumed that the solar energy is available at temperatures at which the collector can deliver it. This assumption may be in contradiction with a conceptual framework which requires that energy be based upon the entropy of the radiation entering the atmosphere. But, except for a solar satellite this energy is not available, and a realistic assessment of the potential of a system must be based on the solar energy available on earth. Using this assumption, Figure 19 illustrates the fraction of United States process heat requirements at different temperatures and corresponding efficiencies for fossil fuel and solar energy systems at temperatures up to 460°F.

Once having performed the end-use matching procedure for a given task and a given location with various solar technologies, it is then possible to select that technology which will give the largest number of Btu's per year per dollar of investment, and then compare the best solar option with the cheapest available fossil fuel. In those cases where the solar option is less expensive than the fossil fuel, investment strategy is, of course, clear. However, the proposed methodology would also permit an examination of various types of incentives which could be used to affect the relative price of the solar or fuel option. Unfortunately, economic comparisons, although of importance, do not result in a unique answer because the economic parameters are subject to uncertainties and allow a number of scenarios.

To illustrate in more detail how the procedure operates, the city of Brownsville, Texas will be examined. The graph in Figure 20 shows the number of industries by SIC code that fall in various temperature ranges and the cost of delivering that energy via a solar system. Then a particular industry, such as milk processing, can be selected, and the cost of various options to meet the energy demand of that plant examined. This is illustrated in Figure 21.

In an effort to compare the end-use matching procedure with an analytical approach, and to provide an analytical guideline how to improve design criteria, one particular unit was examined from a first and second law viewpoint.

First Law Analysis

Consider a steam generator system which consists of a solar collector connected via a closed liquid loop to a heat exchanger in which the water stream, $\dot{m}$, is evaporated. The arrangement is shown schematically in Figure 22. In the solar collector the single phase fluid steam $\dot{m}_c$ is heated from T_1 to T_2. In the bottom portion of the loop, the collector fluid $\dot{m}_c$ is cooled from T_2 back to T_1 by thermal contact with the water stream evaporating at a constant temperature $T_4 = T_3$.

A first law analysis of this solar steam generator reveals the dimensionless groups describing the operation of the system. For the solar collector, we can write

$$I'' A_c = \dot{m}_c C_p \, (T_2 - T_1) + Q_L \ , \tag{1}$$

where I" and A_c are the insolation per unit area and collector area, respectively. Parameter Q_L is the heat loss from collector to atmosphere,

$$Q_L = \bar{U}_c A_c \, (T_2 - T_0), \tag{2}$$

with the average heat transfer coefficient $\bar{U}_c$ assumed constant over a limited range of collector temperatures. Finally, the energy conservation statement for the collector fluid - water steam heat exchanger can be written as

$$\dot{m} \, h_{fg} = \dot{m}_c C_p \, (T_2 - T_1). \tag{3}$$

The outlet temperature T_1 can be related to T_2 and T_4 by the effectiveness relation,

$$\frac{C_{min} \ (T_2 - T_1)}{C_{min} \ (T_2 - T_4)} \equiv \varepsilon = 1 - \exp(-U_h A_h/\dot{m}_c C_p) \tag{4}$$

in which A_h is the heat exchanger area and U_h its overall heat transfer coefficient based on A_h .

Combining eqns. (1) to (4) one can evaluate the resultant collector temperature

$$\tau_2 = \frac{\mathcal{I} + \varepsilon \, \tau_4 + \dfrac{\mathcal{I}}{\tau_{2m-1}}}{\varepsilon + \dfrac{\mathcal{I}}{\tau_{2m} - 1}} \tag{5}$$

where

$$\mathcal{I} = \frac{I'' A_c}{\dot{m}_c C_p T_o} \tag{6}$$

and

$$\tau = T/T_o \tag{7}$$

Parameter τ_{2m} is the maximum stagnation temperature attained by the collector when $\dot{m}_c = 0$. In this analysis τ_{2m} describes the energy efficiency of the collector. Setting $\dot{m}_c = 0$ in eqn. (1) we find,

$$\tau_{2m} = 1 + \frac{I''}{\bar{U}_c T_0} \tag{8}$$

indicating that the stagnation temperature τ_{2m} increases as the heat exchanger heat transfer coefficient $\bar{U}_c$ decreases.

For convenience in parametric studies, one can define a fourth dimensionless parameter,

$$A_r \equiv \frac{\mathcal{I}}{U_h A_h/\dot{m}_c C_p} = \frac{I'' A_c}{U_h A_h T_o} \tag{9}$$

Parameter A_r represents the collector size relative to the size of the two-steam heat exchanger. In conclusion, the system behavior is dictated by four dimensionless parameters, τ_4, τ_{2m}, $\mathcal{J}$ and A_r.

Second Law Analysis

A second law analysis of the same system illustrates the degree of thermodynamic irreversibility and the manner in which various system parameters influence the overall system irreversibility. In a control volume including only the collector and the heat exchanger, the rate of entropy generation is

$$S_{gen} = \dot{m}\, s_{fg} + \frac{Q_L}{T_0} - \frac{I''\, A_c}{T_2} \qquad (10)$$

As indicated by the last term in eqn. (10), the insolation heat transfer $I''A_c$ enters the system at the collector temperature T_2. Therefore, this expression does not include the entropy generation associated with the heat transfer between the sun and the solar collector. The latter contribution is present in nature regardless of whether or not man uses a steam generation arrangement as in Figure 22. Consequently, the sun-collector heat transfer irreversibility is not included in the analysis since it is not caused by the system in the same sense as the collector-atmosphere heat loss irreversibility.

Based on the analytical results developed above, the rate of entropy generation is normalized with respect to $\dot{m}s_{fg}$ by defining the entropy generation number (4)

$$N_s = \frac{S_{gen}}{\dot{m}s_{fg}} = \frac{\tau_4}{\varepsilon\,(\tau_2 - \tau_4)} \left(\frac{\tau_2 - 1}{\tau_{2m} - 1} - \frac{1}{\tau_2} \right) + 1 \qquad (11)$$

τ_2 is given by eg. (5) and ε by eg. (4). The entropy generation number depends on the four parameters obtained in the First Law analysis, i.e. τ_4, τ_{2m}, $\mathcal{J}$ and A_r.

Figure 23 illustrates the relationship between system irreversibility and parameter $\mathcal{J}$, for $\tau_4 = 1.5$, $\tau_{2m} = 3$ and discrete values of A_r. It is clear that the rate of entropy generation decreases in the direction of decreasing $\mathcal{J}$. Physically, this corresponds to the limit when the collector flowrate is so high that the collector assumes the lowest temperature possible.

Figure 23 also illustrates the effect of A_r on N_s. The irreversibility of the system decreases as A_r decreases, i.e. when the heat exchanger surface becomes increasingly larger than the collector surface. Since the factors which reduce irreversibilities require large equipment and capital investments, the optimization of systems to be installed will require the inclusion of economic factors.

Concluding Remarks

This paper has presented a brief review of various solar technologies and outlined a method, called end-use matching, for introducing solar energy into the total energy infrastructure at minimum cost. It then illustrated end-use matching by applying it to solar industrial process heat where near-term replacement of fossil fuels by solar energy appears possible on a large scale. Finally, an example of a first and second law analysis for a solar steam generation system was presented and the pertinent design parameters were derived.

To gain an appreciation of the potential of solar industrial process heat, Figure 19 gives a comparison of the second law efficiency for the utilization of solar energy in the process heat sector between 100° and 500° F with the efficiency of a fossil fuel option. In this comparison, the second law efficiency for the solar energy systems was based on the premise that the solar collector provided the heat at the temperature needed for the task. From a strictly thermodynamic point of view, one might argue that the source of the energy, namely the sun, should have been included in this analysis and that the solar temperature of 5,800° K should be used as the source temperature. Although from a purist's point of view this argument is valid, from a practical engineering point of view it seems more useful to base the efficiency on the ratio of energy necessary to perform the task to the maximum available energy from the equipment that is used. Obviously a piece of equipment that could restore the original sun temperature, although theoretically conceivable, is not a realistic alternative. As mentioned previously, however, end-use matching does take the potential of the sun into account by looking not at one but at several types of solar technology, each of which is capable of achieving a temperature range. However, for achieving higher temperature ranges, a premium price must be paid for the construction and operation of the equipment that is capable of the higher degree of availability required.

When looking at the fossil fuel option, it might also be argued that the fossil fuel system could be degraded so that it would operate at lower temperatures. This, however, would be contrary to common sense because with standard equipment it is usual to achieve the temperature assumed in this comparison. To lower the temperature, one could, of course, decrease the combustion efficiency, add air to the combustion gases, or do something else to lower the temperature. However, no professional engineer would propose to do this.

Another point to consider is that to base availability on the total available energy of the sun would end up in a purely philosophic position but not in an engineering position. All types of fuels that we use today, whether they be direct conversion, solar energy, or fossil fuel, have originally come from the sun. Classical thermodynamics, not having a time scale in its repertoire of variables, cannot account for the difference between using the insolation in steady state and using solar energy stored in fossil fuels. But since we cannot wait for another batch of fossil fuels to mature before tackling our energy problems, we must conclude that thermodynamics, whether it be the first or second law, cannot by itself provide a valid comparison between one option and another. It can, however, provide a guide to the best directions and actions for improvement in the efficient use of available energy sources. In essence, this is the intent and challenge of the solar end-use matching methodology.

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LIST OF FIGURES

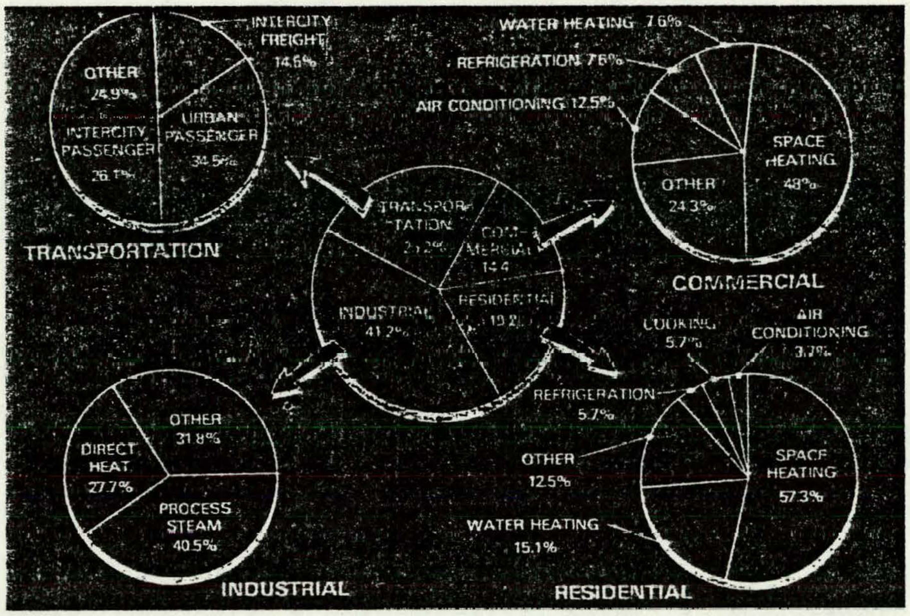


FIGURE 1. Distribution of Primary Energy Utilization in the U.S. in 1976.

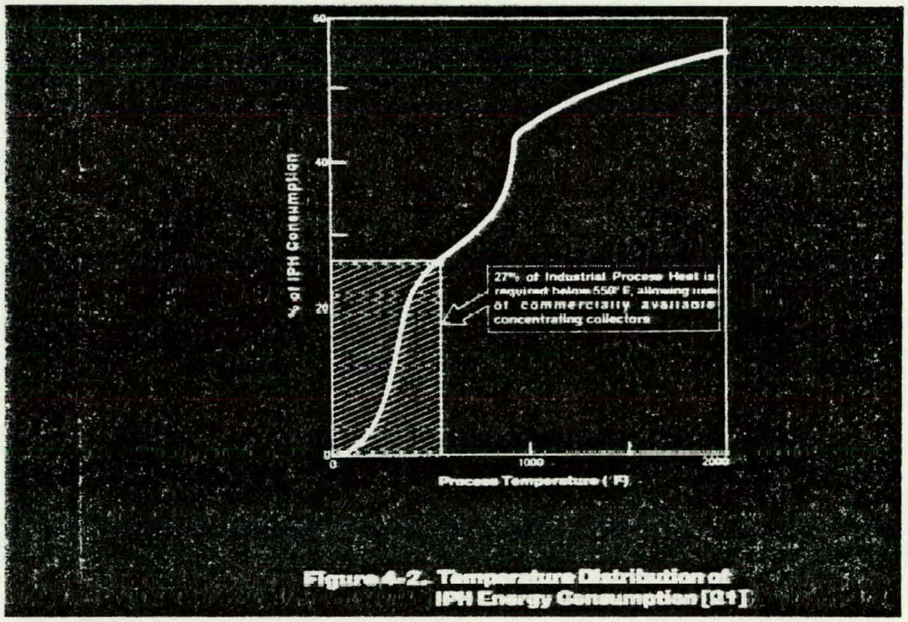


FIGURE 2. Temperature Distribution of Industrial Heat Consumption in the U.S.

FIGURE 3. Photograph of Flat Plate Collector System.

FLAT PLATE COLLECTOR

$$\eta = \frac{Q_u}{IA} = \frac{\tau\alpha IA - UA(T_c - T_o)}{IA}$$

$$\eta = \tau\alpha - \frac{U}{I/\Delta T}$$

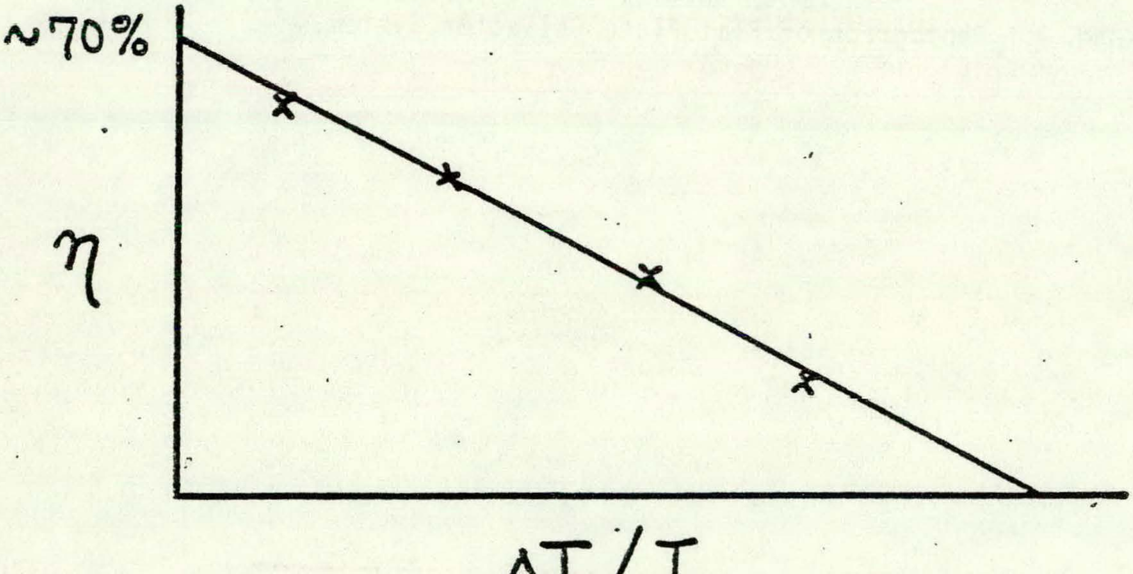


FIGURE 4. First Law Efficiency for a Flat Plate Collector, η_c, vs. Temperature Difference between Collector and Environment divided by Insolation, $\Delta T/I$.

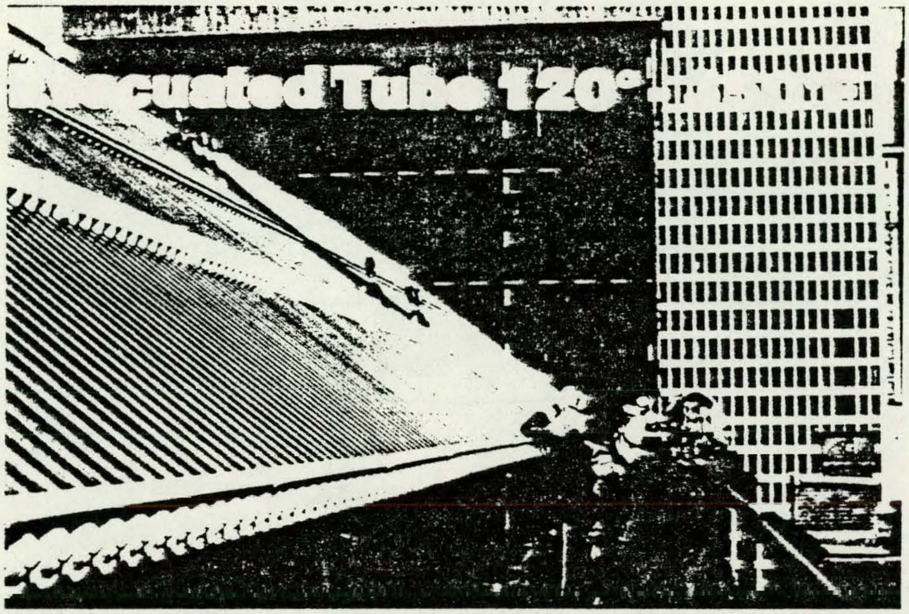


FIGURE 5. Photograph of Evacuated Tube Collector System.

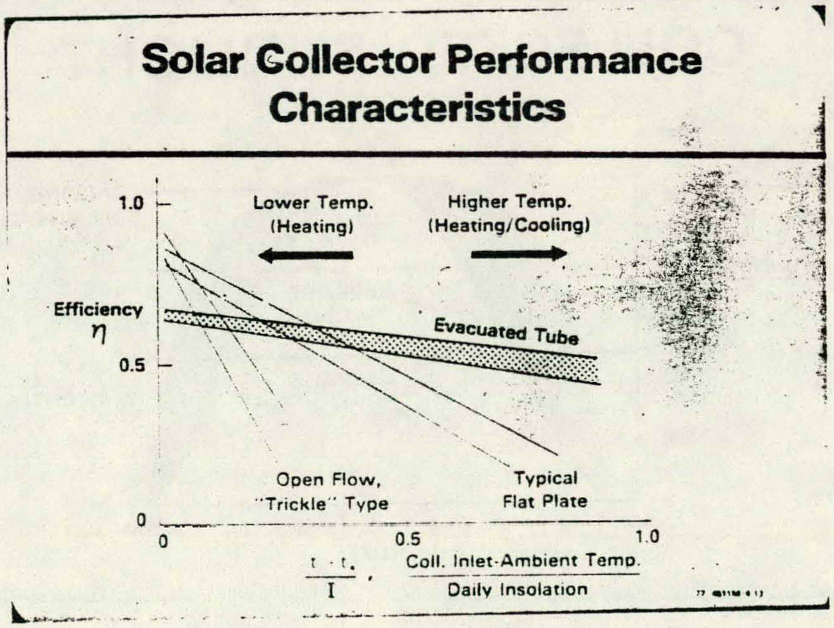


FIGURE 6. First Law Efficiencies for Various Stationary Solar Collectors.

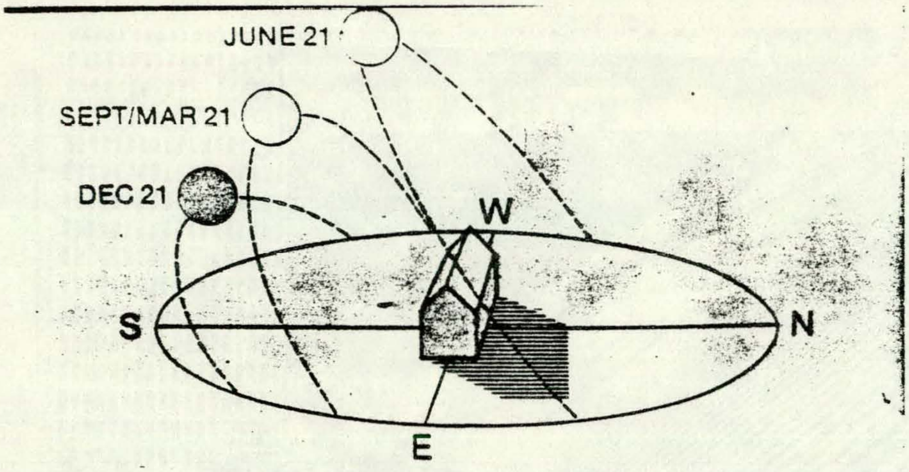


Figure 1-9: **The sun's path across the sky at various times of the year.**

FIGURE 7. Schematic Diagram Showing Apparent Motion of the Sun.

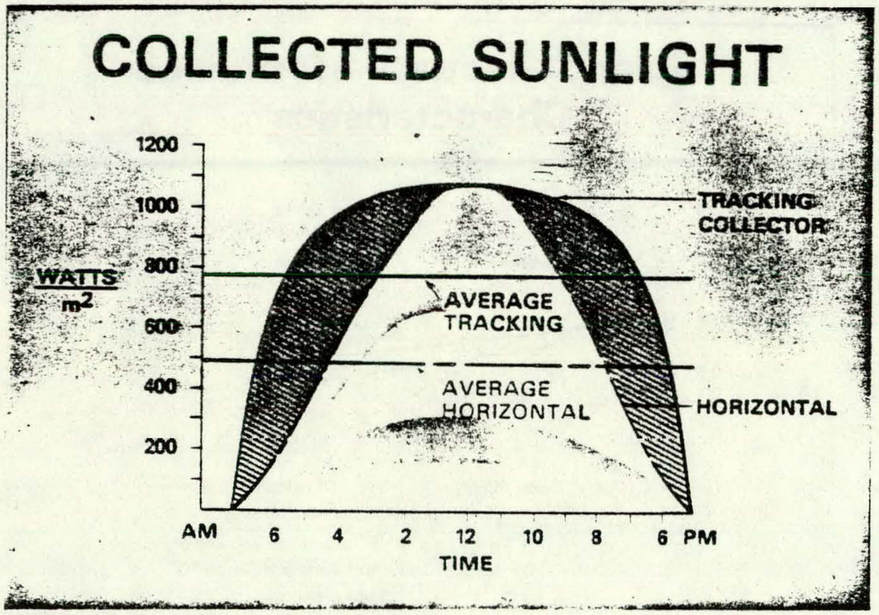


FIGURE 8. Collectible Solar Energy for Various Types of Tracking Mode vs. Time of Day.

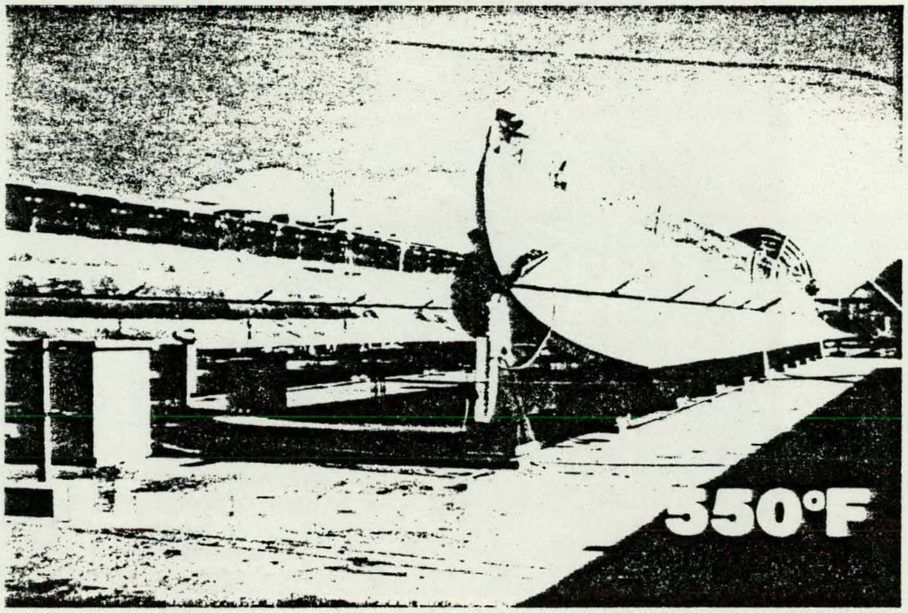


FIGURE 9. Photograph of Linear Parabolic Trough, Single Axis Tracking System.

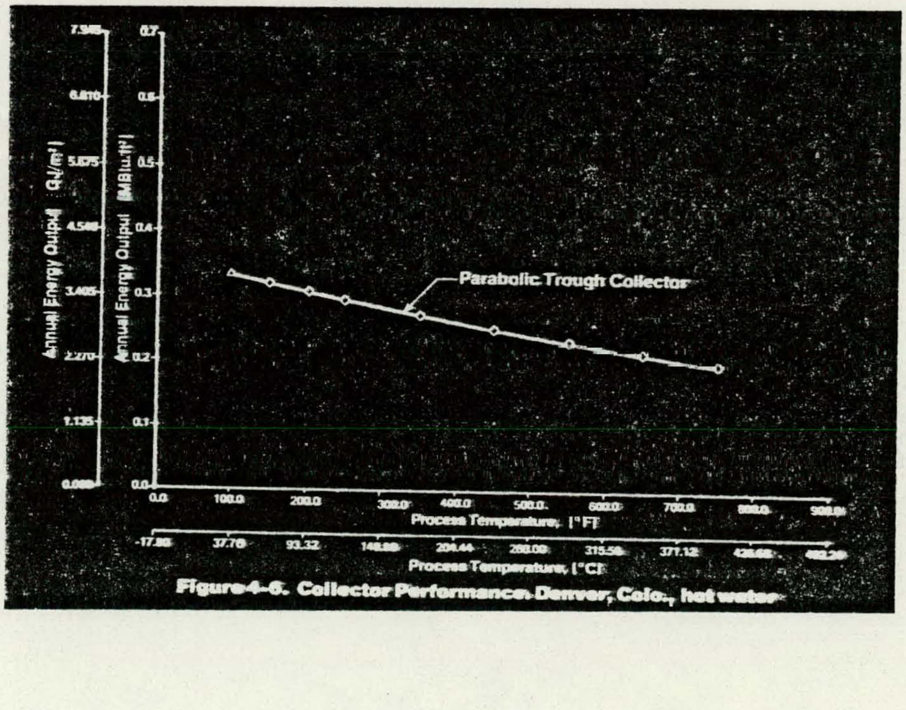


FIGURE 10. Yearly Deliverable Energy from a Single Axis Tracking, E-W Parabolic Trough Collector vs. Delivery Temperature.

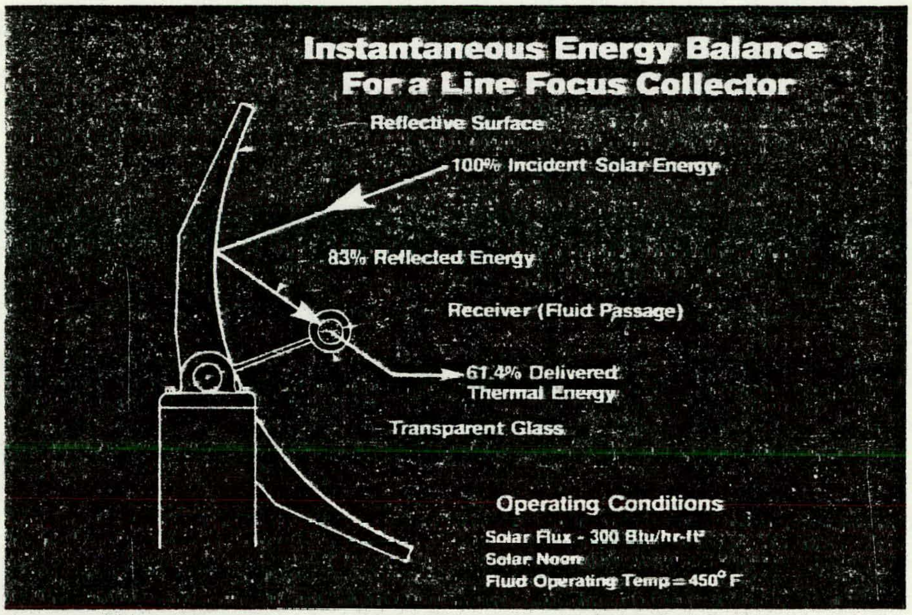


FIGURE 11. Energy Loss Mechanisms for a Single Axis Tracking Parabolic Trough Reflector with Evacuated Tube Absorber.

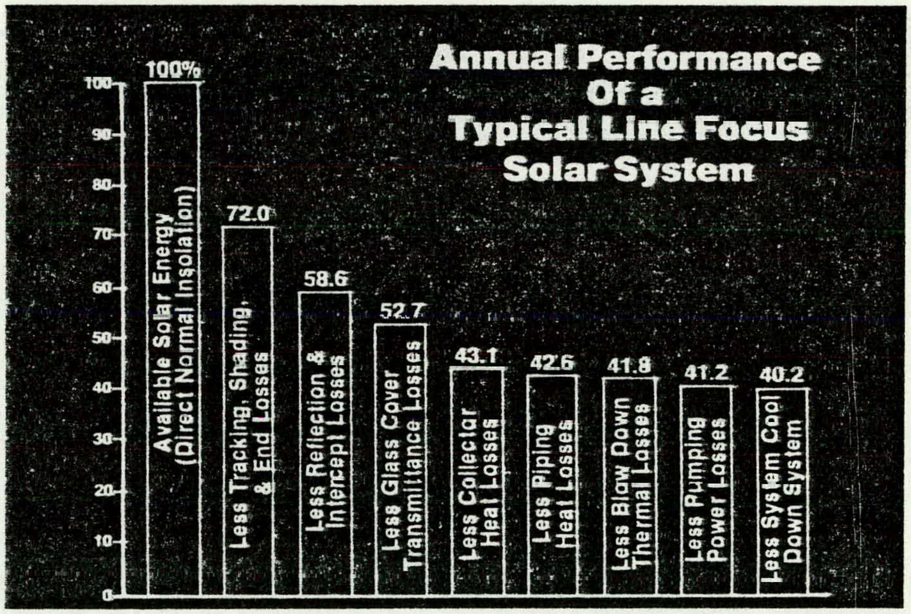


FIGURE 12. Typical Losses and Annualized Delivery of Heat for a Single Axis Tracking Parabolic Trough Type Solar Collector.

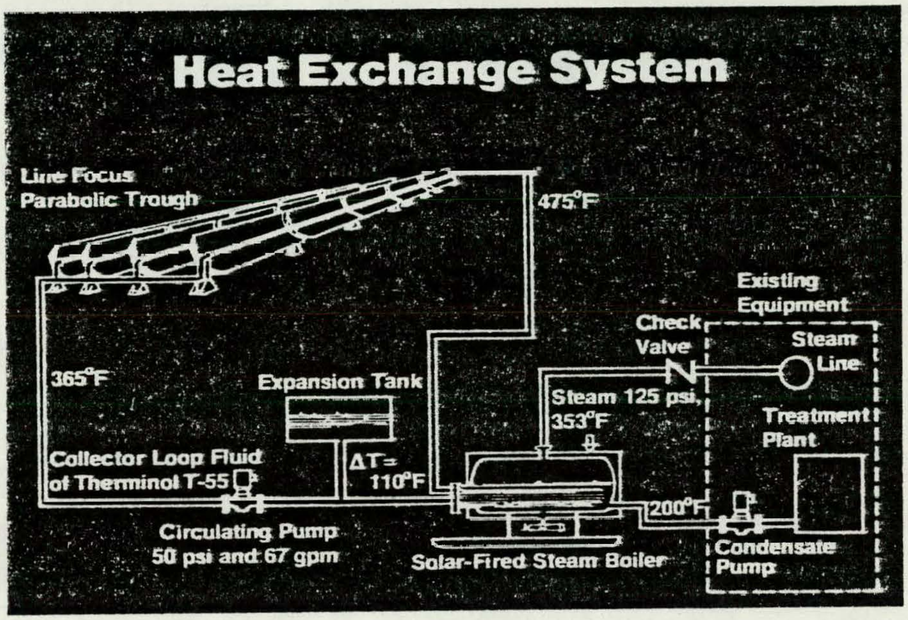


FIGURE 13. Schematic Diagram of Heat Exchange System for a Process Steam Application.

Component Cost	1978	1985	2000
Collector cost ($/ft^2)	10 to 30	8 to 20	7
System cost ($/ft2)	20 to 60	15 to 20	10
Energy cost ($/MBtu)	10 to 12	6 to 8	4
Annual output in sunny location (Btu/ft^2)	300,000	330,000	400,000

FIGURE 14. Efficiencies and DOE Cost Goals for the Years 1978, 1985, and 2000 for Installed Solar Industrial Process Heat Systems.

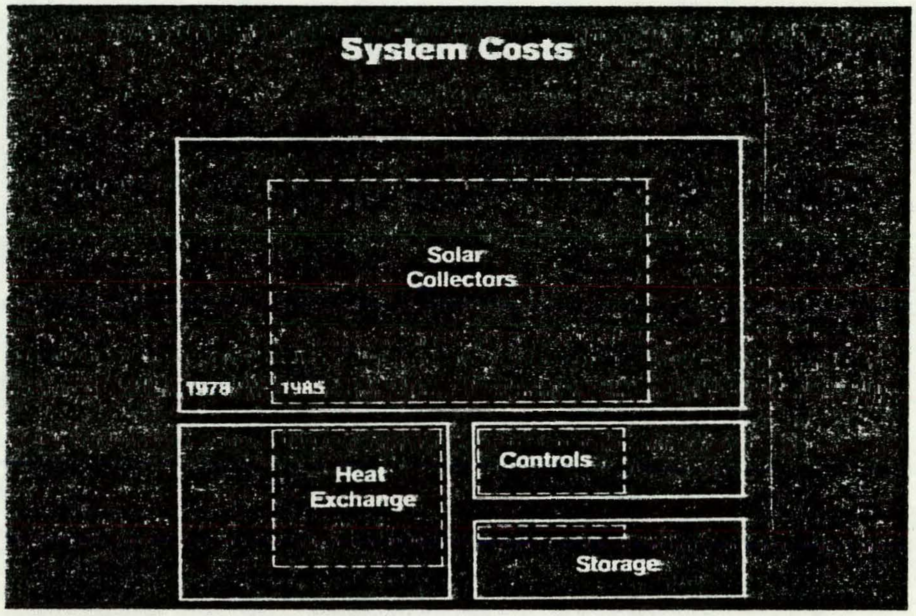


FIGURE 15. Cost Breakdown for a Typical Industrial Process Heat System. (Note that the Major Cost Item is the Collector Field.)

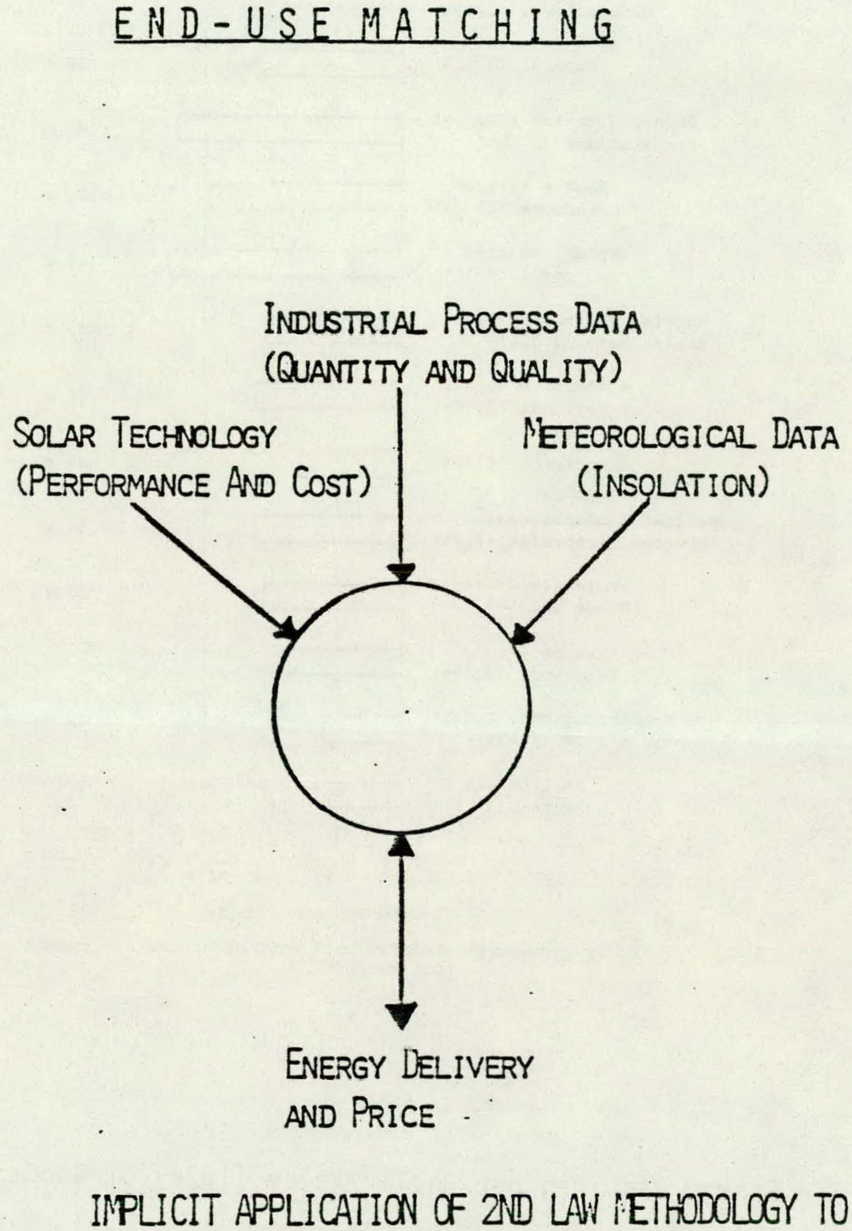
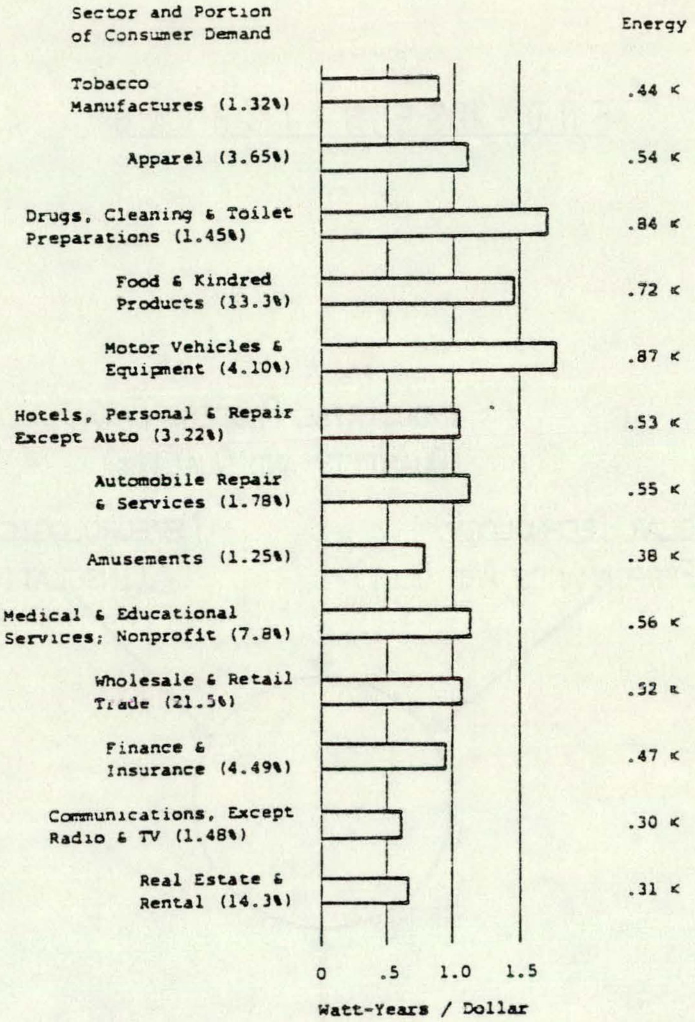


FIGURE 16. Schematic Diagram Illustrating End-Use Matching Methodology.



Energy required per dollar value of goods or services, κ = energy per year/GNP.

FIGURE 17. Energy Required per Dollar Value (1976) of Goods and Services (Ref. 3).

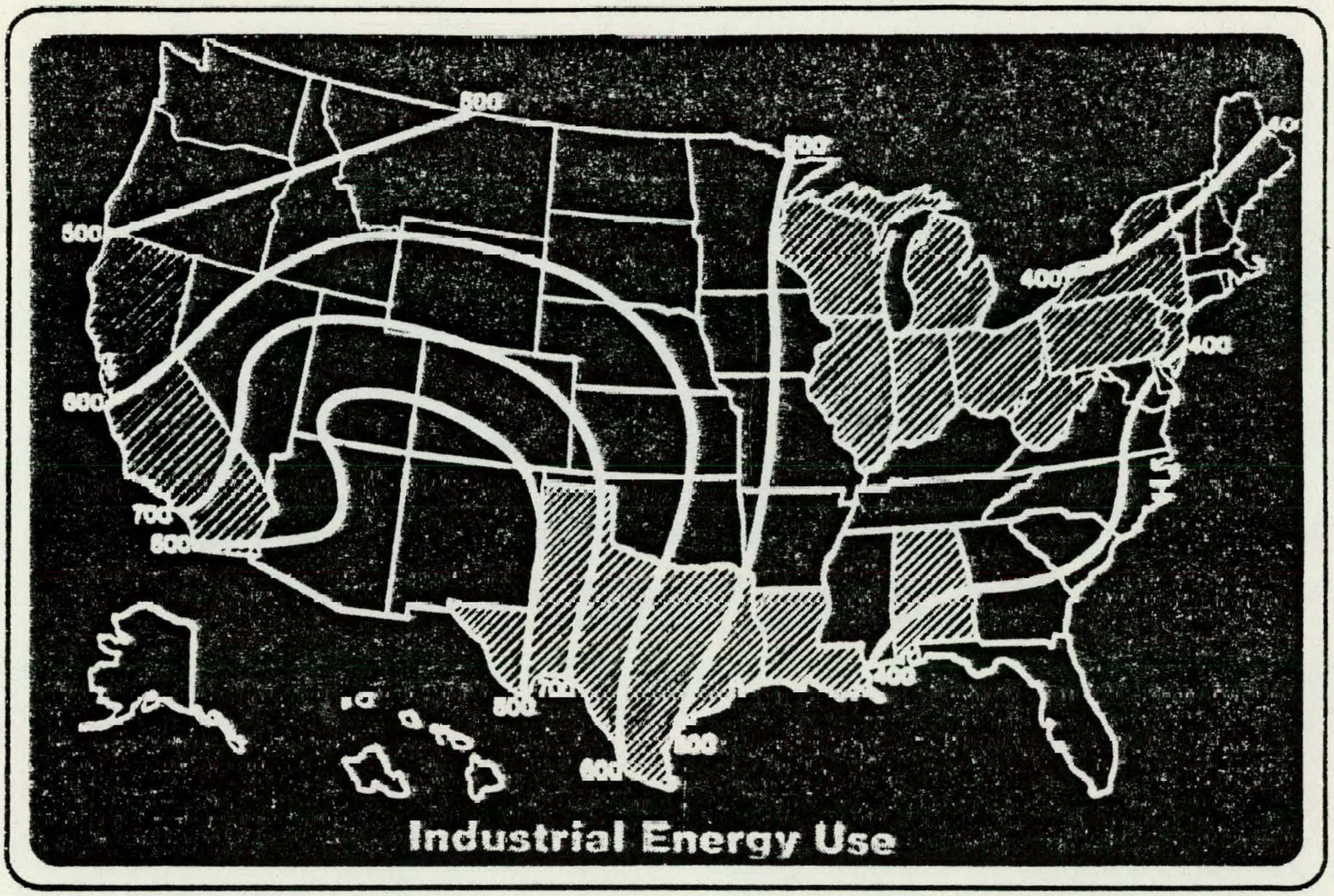


FIGURE 18. Distribution of Insolation Levels in the U.S. (numbers are in 1000's Btu/ft^2-yr) and major IPH Users (shaded areas use 80% of total IPH energy).

Second-Law Efficiencies for U.S. Industrial Processes below 500°F (260°C)

Temperature, °F	Fraction of U.S. process heat, %	Fossil fuel η_2, %	Solar η_2, %
85	10	< 1	12
120	5	6	52
150	5	10	65
175	5	13	71
210	5	16	72
250	5	20	77
300	5	25	83
370	5	30	85
460	5	35	85
Totals/averages	50	16	61

FIGURE 19. Second Law Efficiencies for U.S. Industrial Processes below 500°F (260°C).

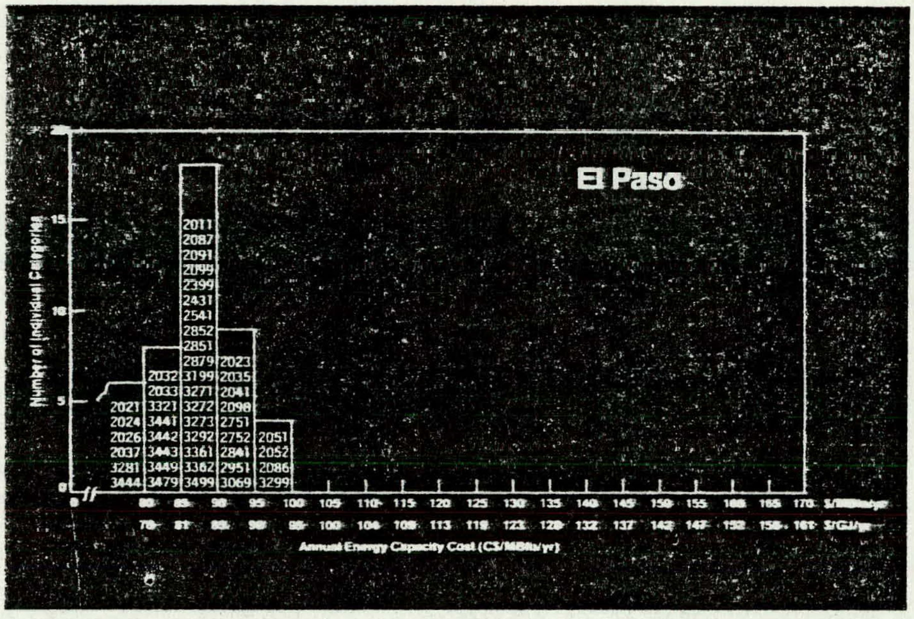


FIGURE 20. Number of Industries by SIC Code in Various Temperature Ranges and Cost of Energy Delivery Estimated for El Paso, Texas.

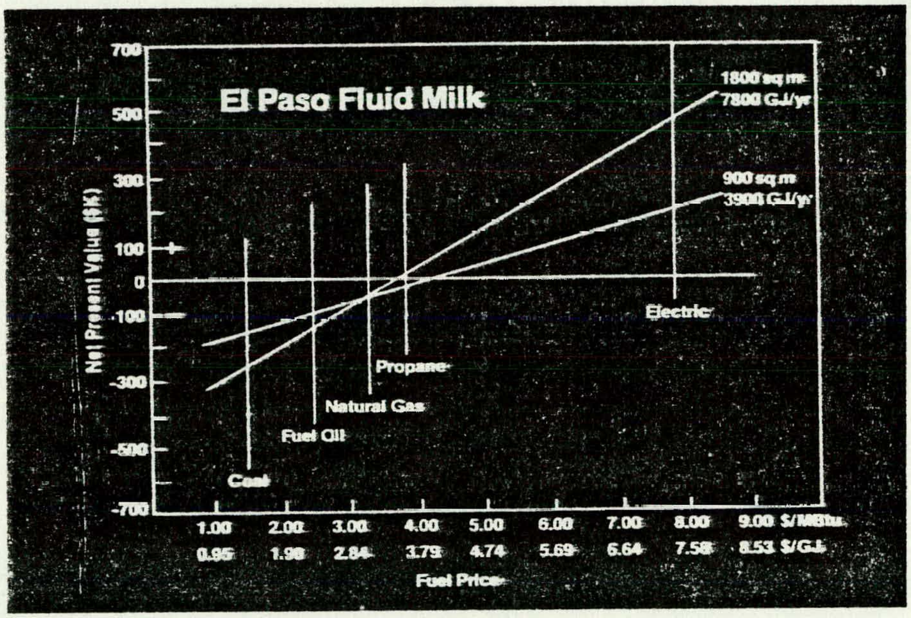


FIGURE 21. Estimated Cost of Energy Delivery in El Paso for a Milk Processing Plant.

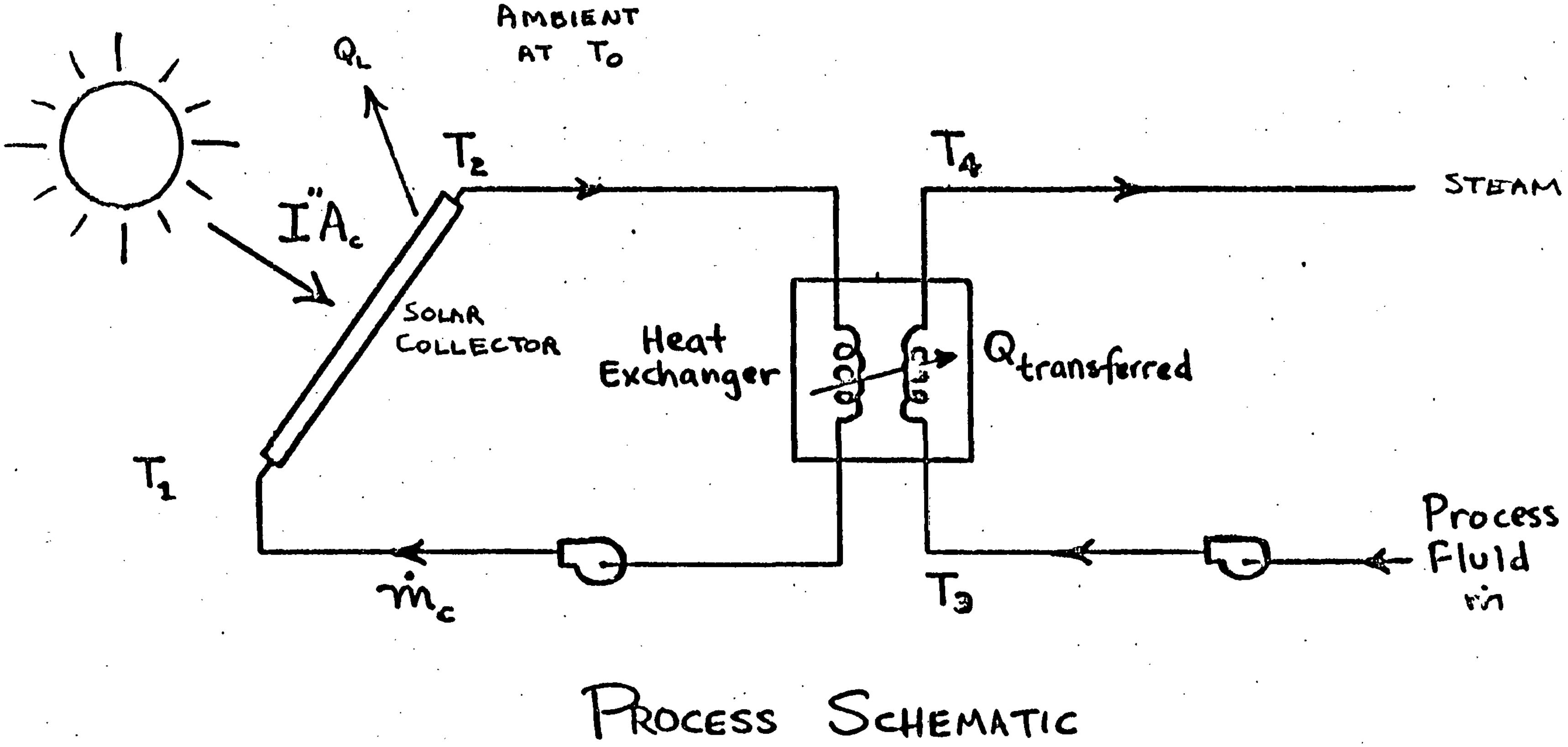


FIGURE 22. Schematic Diagram of a Solar Steam System Using Indirect Heat Exchange.

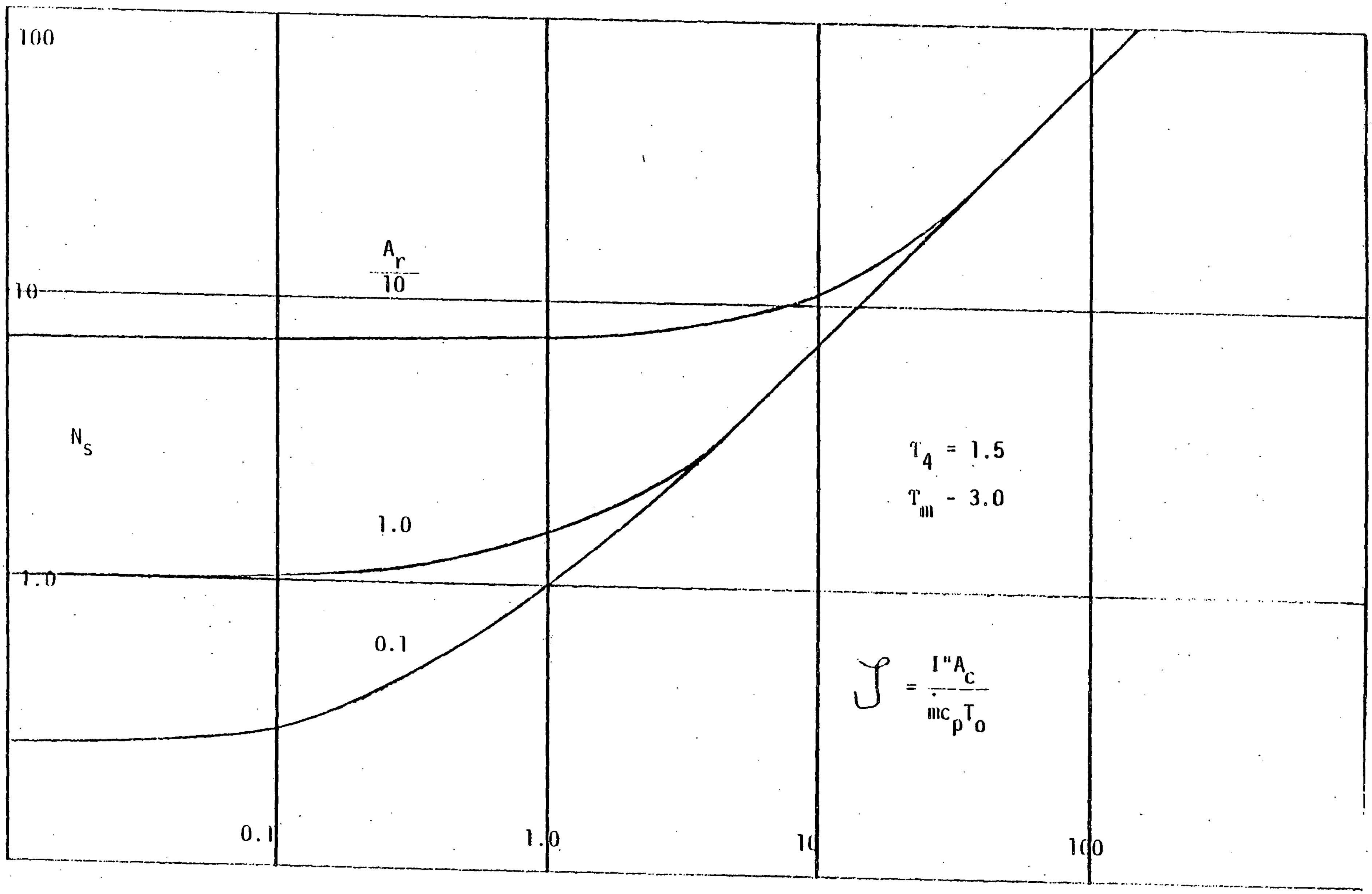


FIGURE 23. Entropy Generation for a Solar Steam System as a Function of $\mathcal{J}$.