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Publication Date

1977-07-01

00194699388

Submitted to Solar Energy

uc-62

LBL-6354 c./

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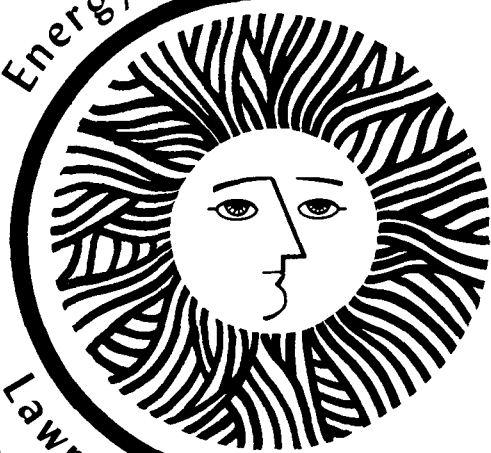
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Effects Of Solar Data Accuracy On The
Performance And Economics Of Solar
Energy Systems

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Donald Grether and Michael Wahlig*

July 1977

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Prepared for the U.S. Energy Research and Development Administration under Contract No. W-7405-ENG-48

LBL-6354
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EFFECTS OF SOLAR DATA ACCURACY
ON THE PERFORMANCE
AND ECONOMICS OF SOLAR ENERGY SYSTEMS*

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ABSTRACT

The effects of designing solar systems using inaccurate solar radiation data have been examined. The primary effect is that the energy output of the solar system, and the corresponding cost of energy, will be proportionally greater or less than expected. The constant of proportionality between the fractional solar data error and the fractional output error ranges from 0.2 to 1.0 for the examples studied. A secondary effect is that the system cannot be optimized correctly with inaccurate values of solar input data. This effect leads to net increases in the cost of energy produced which amount to 2% in the worst case examined. Domestic space and water heating and solar thermal electric conversion are used as examples to illustrate the effects.

INTRODUCTION

The accuracy required for solar radiation data should be determined, at least partially, by the consequences resulting from the use of inaccurate data. In general, one strives to obtain data which are as accurate as possible. However, stringent data requirements lead to excessive costs for

large numbers of sophisticated data stations. The goal of this paper is to delineate and quantify the effects of using inaccurate data; such analyses will assist in the formulation of goals for solar data accuracy.

The primary effect of inaccurate solar radiation data is that the net amount of energy to be produced over the lifetime of a system cannot be accurately predicted. One might think that uncertainties in net energy production would be identical percentage-wise to the uncertainties in the solar data, but this is not the case. For example, it will be shown that, for domestic heating systems of conventional solar design, the uncertainty in energy produced is only half the uncertainty in input solar radiation; i.e., $\pm 20\%$ errors in input lead to $\pm 10\%$ errors in output. This effect is a result of various non-linearities in the system, the most important of which is due to energy overflow from storage.

A secondary effect of using inaccurate solar data is more subtle than the primary effect, but leads directly to increased energy costs. This is in contrast with the primary effect which leads only to cost uncertainties. The secondary effect is a result of designing a solar system for optimal operation (minimum cost) using incorrect values of the solar radiation data. As a consequence of this "incorrect" design, net energy costs are increased by an amount proportional to the square of the error in the solar data.

In this paper dimensionless parameters α and β will be introduced to quantify and primary and secondary effects, respectively. Specific values of these parameters will then be derived for domestic solar heating systems and for solar thermal power plants.

DERIVATION OF THE SENSITIVITY PARAMETER

1. General Considerations

From a systems point of view a solar system is an energy conditioning device which accepts input energy in the form of solar radiation and produces output energy in the form of useful heat, electricity, or some other form. From this point of view it is desirable to describe the sensitivity of output to input on purely general grounds, without reference to the specific details of each system.

Let E_s represent the annual average usable energy produced by a solar energy system, and let I be the annual average input insolation. The insolation I can be the radiation received by a horizontal surface, the direct normal radiation, or other relevant solar input. We want to examine the response of the system when the input is increased or decreased. We can denote the fractional change in the input by the symbol δ :

$$\delta = \Delta I / I. \quad (1)$$

This increment of the annual input should be understood to consist of a fixed fractional increase or decrease, independent of time of the day or year.

Next, the sensitivity parameter, α , which relates the change in output energy to the change in input insolation level, can be expressed as:

$$\alpha \equiv \frac{\Delta E_s / E_s}{\Delta I / I} \quad (2)$$

Or, equivalently, combining eqns (1) and (2), one obtains:

$$\frac{\Delta E_s}{E_s} = \alpha \delta .$$

The annual output E_s , compared to the nominal output $E_{s,0}$ for $\delta = 0$ may be deduced from eqns (1) and (2):

$$E_s = E_{s,0} (1 + \alpha \delta). \quad (3)$$

Equation (3) is just a series expansion for E_s in powers of δ , terminated after the first two terms.

For the purposes of this article, δ will represent the error in the incident solar radiation, and multiplication by the sensitivity parameter α will convert this to an error in the calculated value of the system output energy. For example, if $\alpha = 0.5$, and the original solar data used in the system design was 20% too high, the situation may be described by a change of -20% in the input ($\delta = -0.2$). In this case, eqn (3) shows that 10% less energy than anticipated will be produced or, equivalently, that the unit cost of solar energy (in this example) will be increased by 10% (assuming that the annual operating cost is independent of the amount of energy produced).

Before presenting values of α for different solar systems it is worthwhile to make some statements regarding the values which α can assume. The efficiency η of the solar system is given by the relation

$$E_s = \eta I, \quad (4)$$

and hence with eqn (2) the sensitivity α can be written in the form

$$\alpha = 1 + \frac{\Delta\eta/\eta}{\Delta I/I} \quad (5)$$

Thus, to the extent that the efficiency is independent of the input power level I , α is equal to unity. If the efficiency decreases with I , α will be less than unity. This line of reasoning can be pursued a little further by writing the overall efficiency as the product of subsystem efficiencies,

$$\eta = \eta_1 \eta_2 \cdots \eta_N \quad (6)$$

and substituting in eqn (5):

$$\alpha = 1 + \sum_{i=1}^N \frac{\Delta\eta_i/\eta_i}{\Delta I/I} \quad (7)$$

This equation permits one, in principle, to compute α as a sum of terms each of which refers primarily to a component subsystem. It will prove useful for the analysis of solar thermal electric conversion.

Another general observation regarding α is the following. Consider, for simplicity, a domestic heating system. If f_s , the fraction of the load provided by solar energy, is very large ($f_s \approx 1$), much of the collected energy must be discarded. This is particularly true of the incremental heat available, if the insolation I is increased. Thus, from eqn (2), α is small because ΔE_s is small. More generally, one has

$$\alpha \rightarrow 0 \text{ as } f_s \rightarrow 1 \quad (8)$$

This limit applies to systems in which unlimited amounts of "surplus" energy cannot be stored indefinitely.

2. Application to Domestic Space and Water Heating (DSWH)

The method employed to estimate α for DSWH systems was to carry through standard design procedures to estimate the solar heat produced by systems of conventional solar design. Two California climates were considered (Davis and Los Angeles), and two design methods were employed. With each method and for each climate, the solar input was varied parametrically from its nominal value and α was computed from eqn (2).

The specific design techniques employed were those developed by J. D. Balcomb et al. at Los Alamos (the LASL simplified method [1]), and by C. Barnaby of the Berkeley Solar Group (BSG). The BSG method is based upon the "utilizability curve" approach originally discussed by Hottel and Whillier [2] and extended by Liu and Jordan [3].

Both procedures were used to analyze the performance of solar heating systems for a house of 138 m^2 (1500 ft^2) floor area and a heating load factor of 7.9 kWh per degree-day (Celsius) (15 kBtu per degree-day (Fahrenheit)). In the LASL method the collectors are tilted from the horizontal at an angle equal to the latitude $+10^\circ$, whereas in the BSG program a fixed tilt angle of 45° was employed. For the present purposes, these differences are insignificant.

Figure 1 shows curves of usable solar energy E_s versus collector area as determined from the LASL method. The dashed curves in Fig 1a display the values which are obtained when the solar data are varied from nominal values by $\pm 20\%$. Figure 2 gives more detail; it shows the differences ΔE_s . From

these results it is possible to compute α using eqn (2). The results for α are plotted versus the solar heating fraction f_s in Fig. 3. This plot shows the results for two climates and for both the LASL and BSG computational methods. The simplified design methods are based on entirely different approaches so it is not surprising that there is considerable scatter in the values for α . Also, the methods cannot be expected to be accurate for values of f_s much outside of the range of 0.4 to 0.8. Nevertheless, the behavior $\alpha \rightarrow 0$ as $f_s \rightarrow 1$ is observed as anticipated by eqn (8).

Based on the results shown in Figure 3, it is concluded that, for domestic space and water heating in the climates studied, the sensitivity parameter is given by

$$\alpha = 0.5 \pm 0.2,$$

for values of f_s in the range of 0.4 to 0.8.

3. Application to Solar Thermal Electric Conversion (STEC)

Many of the important losses in a solar thermal electric conversion power plant are of a particularly simple type: they lead to component efficiencies which are independent of the operating power level. Examples are losses due to tracking and aiming errors, shading of mirrors, shading of the receiver(s), and imperfect reflectivities. Each of these losses corresponds to an efficiency which is independent of input power and thus cannot contribute to α in eqn (7).

One type of loss which leads to a component efficiency depending on the operating power level is turbine efficiency. This efficiency is a function of the pressure and temperature of the working fluid, and hence could,

depending upon the details of power plant operation, vary with the input solar radiation level. On the other hand, the operating strategy of the power plant will likely include efforts to keep the turbine efficiency high (and therefore fairly constant), and those efforts would mitigate efficiency variations.

Other losses which depend on the input operating level are the heat wasted due to storage overflow (which will be small for a well-designed plant) and the receiver thermal losses. The corresponding efficiencies will vary only slowly with input power level and will not contribute significantly to eqn (7).

The conclusion of the foregoing discussion is that, for STEC power plants of "conventional" design, the sensitivity parameter is

$$\alpha \approx 1.$$

One major proviso should be attached to this result. Since the marginal cost of producing power (from thermal energy already collected) is very small, it has been assumed that all electricity that the power plant can produce is effectively used. In the case of a utility operating an intermediate load solar power plant, the effective value of α can be much smaller because (economic) credit may not be given for energy produced in the absence of intermediate load demand. If this "unwanted" energy is not counted in the output, values of α can fall to the range of $\alpha \approx 0.2$. Figure 4 shows a plot of change in effective power produced versus change in input solar radiation for a 100 MW_e intermediate load power plant of the central receiver type, with 6 hours of thermal storage. The Figure is adapted from results obtained by the Aerospace Corporation [4], and is constructed from those results by using the fact that, for the Aerospace model, fractional changes in the total heliostat area A cause the same changes in output

as fractional changes in solar input energy. The slope of this graph gives:

$$\alpha_{\text{eff}} \approx 0.24$$

for this power plant which meets 94% of its load ($f_s = 0.94$). The small value of α can be regarded as a consequence of the closeness of f_s to unity (cf. eqn (8)).

CONSEQUENCES OF THE USE OF INACCURATE DATA

The primary consequence of using inaccurate solar radiation data is the actual realization of an output energy level from the solar system that is different from that predicted (using inaccurate data) during the system design. The values of the sensitivity parameter α described above indicate the measure of the difference between expected and actual system output.

Economically, α can be interpreted as the fractional error in cost of energy produced by the solar system, as a result of the use of inaccurate solar radiation data. Thus for the DSWH system, the value of $\alpha \approx 0.5$ indicates that a 20% error in solar data results in a 10% error in the unit cost of the heating energy produced by the solar system. For the STEC system, the range of values of α between 0.2 and 1.0 indicates that a 20% error in solar data would result in an error between 4% and 20% in the unit cost of the solar-generated electricity.

It should be noted that this effect is only an "apparent" cost penalty (or gain) associated with the solar-produced heat or electricity; i.e., this effect results in a difference between the expected and the actually achieved system output. This actual achieved system output will be essentially the

same (see next section) as if the correct solar data had been used to design the system. However, this should not be interpreted as meaning the effect is unimportant. The perception of the expected system output is what is used in the decision-making process, when deciding whether to make the economic investment in the solar system. Use of inaccurate solar data might therefore produce an incorrect decision resulting in a substantial economic penalty from misapplication of capital.

There is a secondary consequence of using incorrect solar data. It is associated with systems that have been optimized using erroneous input solar data, thereby arriving at a non-optimum system design point. Although this effect is smaller in magnitude than the primary consequence discussed previously, this secondary effect results in a real cost penalty. It will be described separately for solar heating systems and solar electric systems in the following subsections.

1. Secondary Effect for Domestic Space and Water Heating (DSWH)

When a solar heating system is optimized using inaccurate solar data, the resulting cost of heating is always equal to or greater than the cost obtained if correct solar data had been used. This can be seen by referring to Figure 5. The Figure displays curves of annual heating cost vs. solar collector area near the minimum in the cost curve. By optimization of the solar system is meant selection of the system parameters so as to operate at this point of minimum cost. The solar collector area is a usual parameter used in the optimization calculation.

Suppose that a solar system were to be optimized using an erroneously high value of solar input data. Then the system would be optimized to

point (a) in Figure 5, and a collector area A'_0 would be selected. However, after the system were built, it would be observed to operate over a long period of time at point (b) instead of (a). If the system had been designed with knowledge of the correct solar data, it would have operated at point (c), the minimum for the true-data curve. The economic penalty associated with this effect is the annual difference in heating cost between points (b) and (c).

Two properties of this effect can be seen from Figure 5. First, the real cost using erroneous data is always equal to or higher than the real cost using correct solar data; i.e., the cost penalty is always positive (or zero). If the minima of the curves in Figure 5 were all in a vertical line, then the cost penalty would be zero. For all other cases, the cost penalty is positive. The second property is that the shape of the curves in Figure 5 near the optimum operating points is quadratic in nature. Thus the cost penalty for the use of inaccurate data is proportional to $(A'_0 - A_0)^2$. Since the error in collector area $(A'_0 - A_0)$ is caused by the solar data error ΔI , these errors can be shown to be proportional to one another. Consequently, the design cost penalty is proportional to $(\Delta I)^2$, and the annual cost of energy C is related to the cost C_0 relevant to "perfect" solar data by the relation

$$C = C_0 (1 + \beta \delta^2), \quad (9)$$

where $\delta = \Delta I/I$ and $\beta = \geq 0$ is a dimensionless number.

The methods used previously to estimate α for DSHW have also been used to estimate β . Figure 6 shows some of the optimization curves obtained for DSHW systems for the Davis and Los Angeles locations. Assumptions used to obtain the annual heating cost were: (i) Solar system cost, \$1,000 plus \$100 per square meter

of collector area; (ii) Auxiliary fuel cost, \$1.50 per 10^8 J (\$1.50 per therm; and (iii) Payback period of 30 years at 9% interest. Values for β for the systems and climates under consideration lead to estimates in the range of 0.1 to 0.5. Using the large values $\beta = 0.5$ and $\delta = 0.2$ (20% data error), one finds from eqn (9) that even in this case the cost penalty is only 2%. Thus the solar data need not be known to high precision in order to produce an economically reasonable design.

2. Secondary Effect for Solar Thermal Electric Conversion (STEC)

The situation for solar thermal electric conversion is slightly different because the auxiliary (back-up) system is not part of the plant, but rather is part of a network. Furthermore, the demand for energy is not fixed at some total annual energy produced. That is, the market share of the power plant(s) depends on the unit cost of power, so that this is the quantity that should be minimized.

It should be further noted that the cost of the auxiliary energy is not known, so that a procedure directly analogous to that used for DSWH cannot be used. Denoting the unit cost of energy by R , one designs for minimum R and consequently obtains

$$R = R_0 (1 + \beta \delta^2), \quad (10)$$

for the same fundamental reasons that eqn (9) was obtained. Use of the same symbol β as appears in eqn (9) should not lead to confusion since they refer to different systems. Furthermore, in both cases β has the same interpretation as a measure of the cost of design error caused by errors in solar data.

An estimate of β has been made using the graph in Figure 4. Since, for the Aerospace model, changes in A are equivalent to changes in I , one can write for the effective solar electricity produced,

$$E_s = E_{s,o} \left[1 + a \left(\frac{A}{A_o} - 1 \right) - b \left(\frac{A}{A_o} - 1 \right)^2 \right], \quad (11)$$

where $E_{s,o}$ and A_o are nominal values, and the constants a and b are evaluated graphically as $a \approx 0.24$, $b \approx 0.45$. The expression for the annual cost of power has the form

$$C_s = C_{s,o} \left[1 + c \left(\frac{A}{A_o} - 1 \right) \right], \quad (12)$$

assumed linear as a function of heliostat area A . The constant c can be determined by using the fact that the minimum in

$$R = C_s / E_s \quad (13)$$

occurs at $A = A_o$. This requires that $c = a = 0.24$.

Consider now the form that eqns (11) and (12) would have if the solar input were changed from its nominal value I_o to $I = I_o (1 + \delta)$. Equation (11) can be rewritten with $A (1 + \delta)$ replacing A , since a change in area is equivalent to a change in I . Equation (12) is unchanged. The resulting equations for R display a minimum at a new value of A , corresponding to the appropriate change in design. From these results the cost penalty for use of solar data in error by the fraction δ can be obtained, after some lengthy but straightforward algebra. Equation (10) is reproduced, with $R_o = C_{s,o} / E_{s,o}$, and

$$\beta = b \left[1 - \frac{a(1-a)}{2b} \right]^2. \quad (14)$$

Substitution of the values of a and b listed after eqn (11) yields

$$\beta \approx 0.3.$$

As in the case of DSWH, the obtained value for β indicates that the design penalty for inaccurate data is not very large: only about a 1% cost penalty for a 20% data error. In different power plant designs or different climates β will of course vary. But it would be surprising if it were to become much larger than unity.

SUMMARY

The secondary effect--the cost penalty incurred by non-optimum design resulting from the use of erroneous solar radiation data--is found to be relatively small for both domestic solar heating systems and solar thermal power plants. The maximum penalty consistent with the foregoing calculations is of the order of 2% of the cost of power produced.

The primary effect has a larger magnitude. For domestic space and water heating systems in temperate climates α is approximately 0.5, which means that a 20% data error leads to a 10% error in the amount of usable energy produced. For solar thermal electric conversion α varies from 0.2 to 1.0, depending upon the ability of the electric network grid to make effective use of all the power producible by the solar plant. Thus a 20% data error leads to an error in energy output that varies from 4% to 20%, depending upon the specific power plant operational circumstances.

* Work supported partially by the California Energy Resources Conservation and Development Commission and partially by the Environmental and Resource Assessment Branch, Division of Solar Energy, Energy Research and Development Administration.

NOMENCLATURE

- a - constant equal to 0.24
- A - total collector or heliostat area
- A_o - nominal or optimum collector or heliostat area
- A'_o - modified optimum collector area
- b - constant equal to 0.45
- c - constant equal to 0.24
- C - total annual cost
- C_s - annual cost of solar system
- E_s - annual solar energy utilized
- f_s - fraction of the load supplied by a solar system
- I - annual solar input energy (insolation)
- R - unit cost of energy; e.g., C_s/E_s
- α - sensitivity of output to input
- α_{eff} - effective sensitivity when part of the output energy is not utilized
- β - cost penalty coefficient
- δ - fractional change in I

Subscripts

- o - nominal or optimum value
- i - part i of whole system
- s - solar

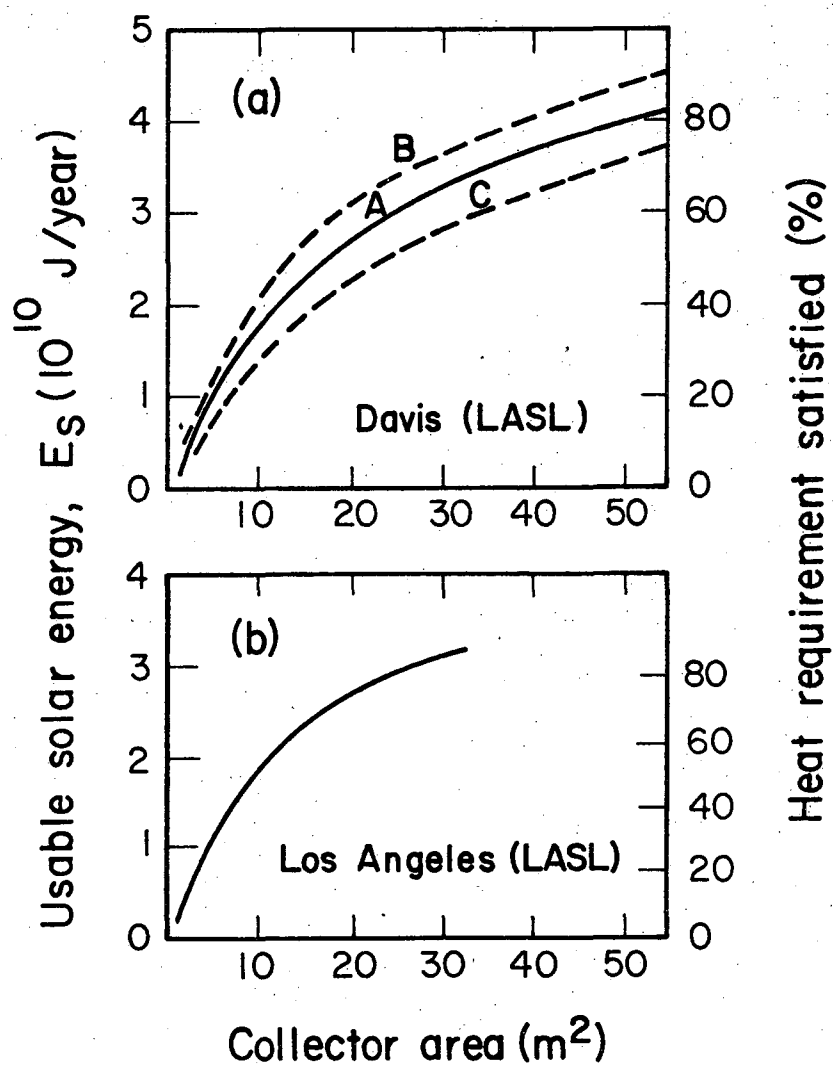
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Figure Captions

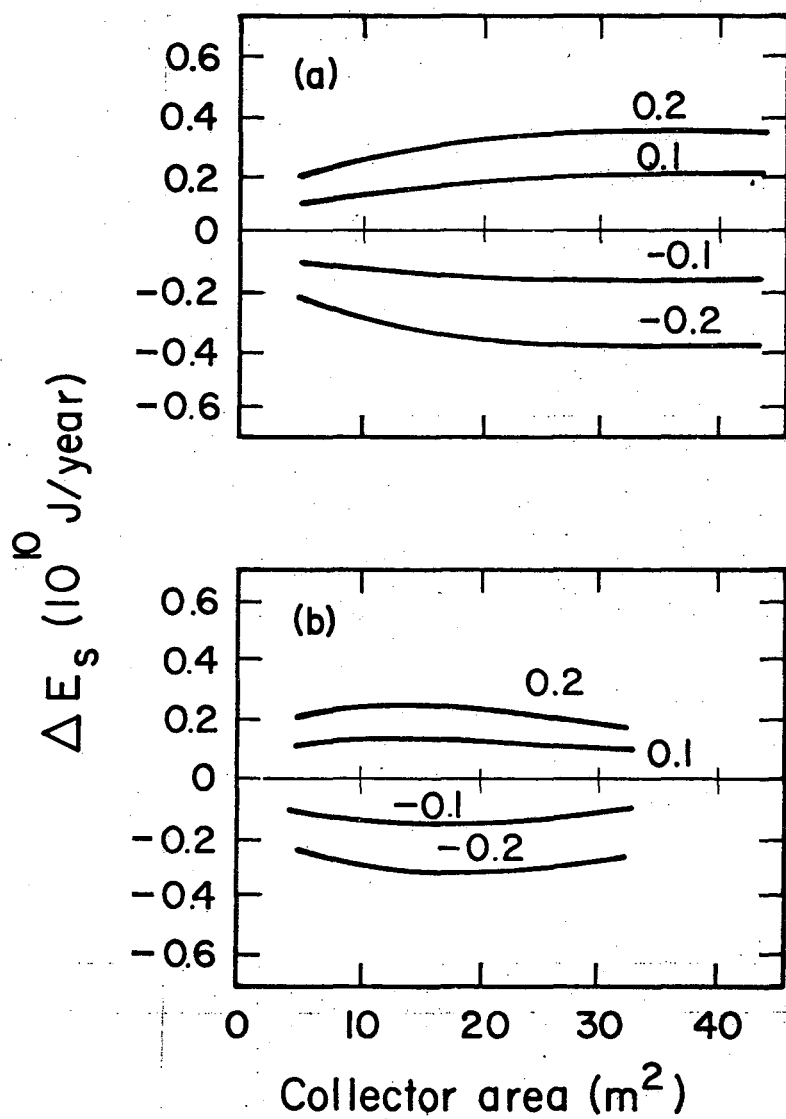
- Figure 1: Plot of usable solar energy E_s as a function of collector area, using the LASL simplified design method. Curve A represents the actual (nominal) long term system behavior. Curve B shows the output that would be obtained if the solar input were larger than nominal by 20% ($\delta = +0.2$). Thus curve B also represents the output that would be predicted if the solar data were 20% too high. Curve C shows the output values for $\delta = -0.2$,
- Figure 2: The difference in annual output ΔE_s as a function of collector area. The curves are labeled with corresponding values of δ , the error in the incident solar radiation.
- Figure 3: The sensitivity parameter α , plotted as a function of the solar heating fraction f_s , for the Davis and Los Angeles climate regions, using both the Los Alamos (LASL) and Berkeley Solar Group (BSG) design methods.
- Figure 4: Percent change in effective power produced versus percent change in input radiation, for a particular power plant with $\alpha = 0.24$. The upper bound of 106% of nominal output power corresponds to the limit at which 100% of the demand for electricity is met.
- Figure 5: Illustration showing the "primary" and "secondary" effects discussed in the text. Solar data that is too high leads to a low prediction for the annual heating cost shown by (a) at a collector area A'_0 . The actual performance of the system is at point (b), and the cost shift between these points is the primary effect. If the correct solar data had been available, the system would have been designed to operate at (c) with collector area A_0 . The annual cost difference between (b) and (c) is the secondary effect.

Figure 6: The annual cost of owning and operating a solar heating and hot water system plotted as a function of collector area for Davis and Los Angeles. Curves are labeled with the appropriate values of δ , corresponding to differing values of input solar radiation. Assumptions regarding cost parameters are given in the text. These results were obtained using the LASL design method.



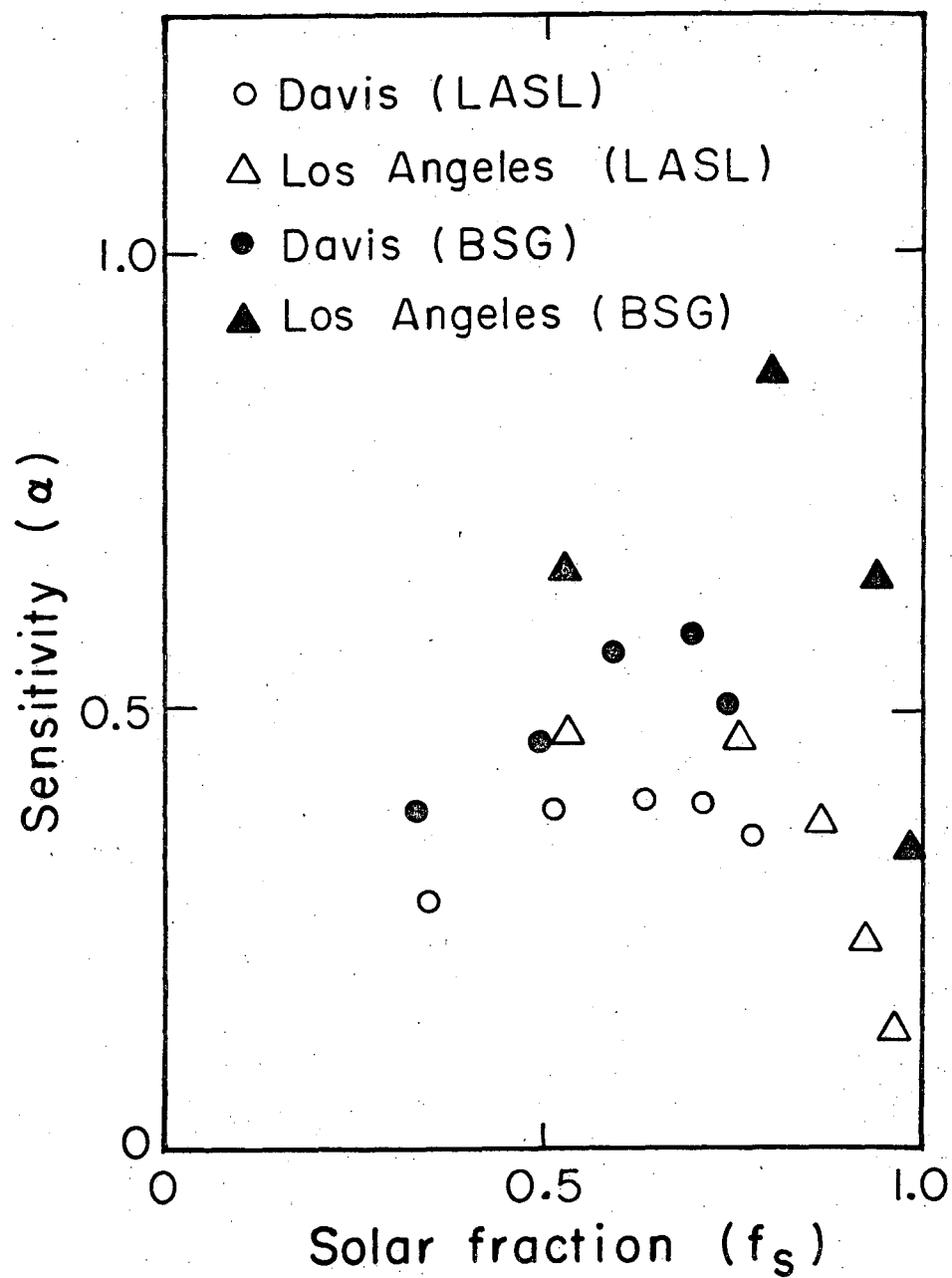
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Fig. 1



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Fig. 2



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Fig. 3

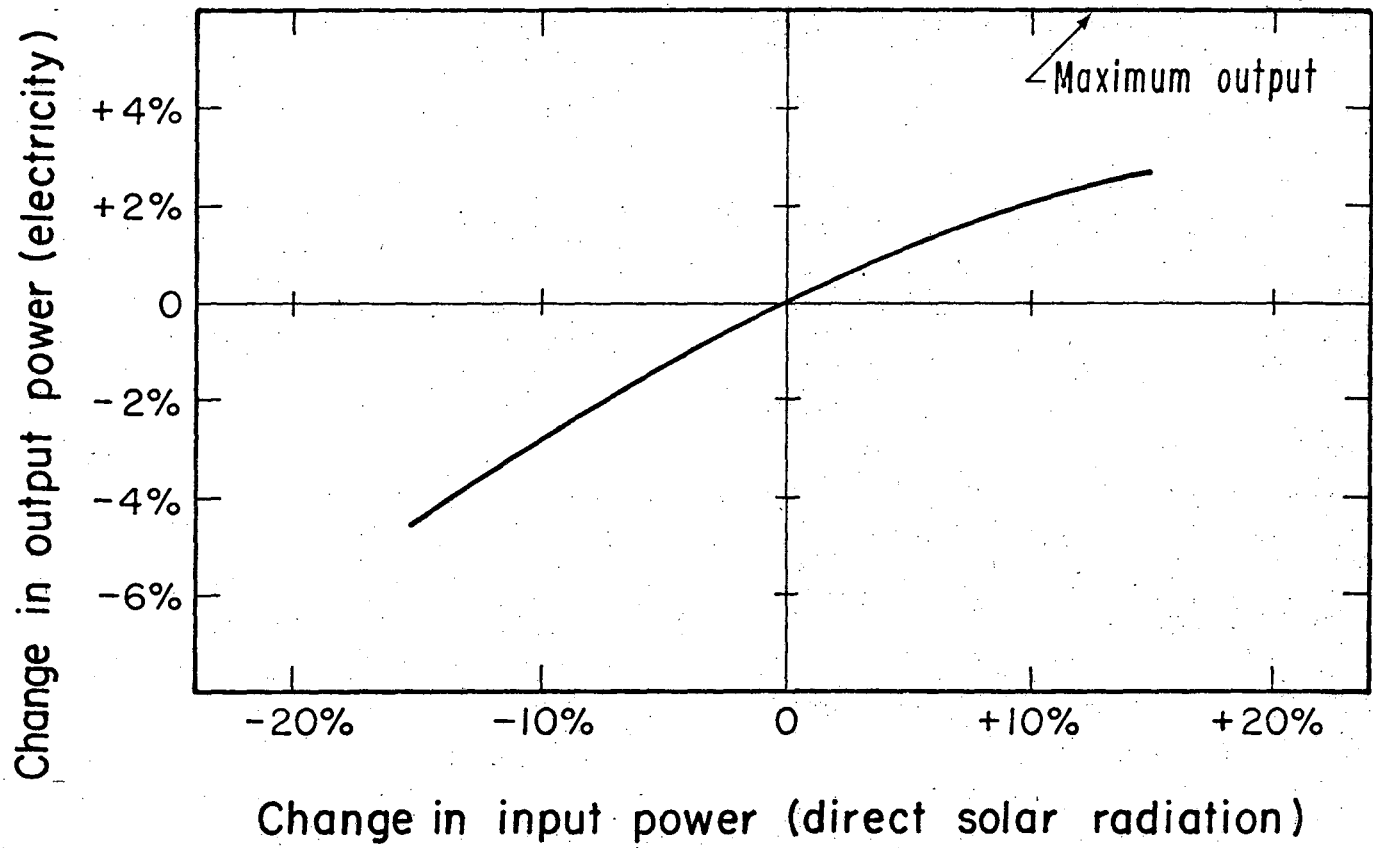


Fig. 4

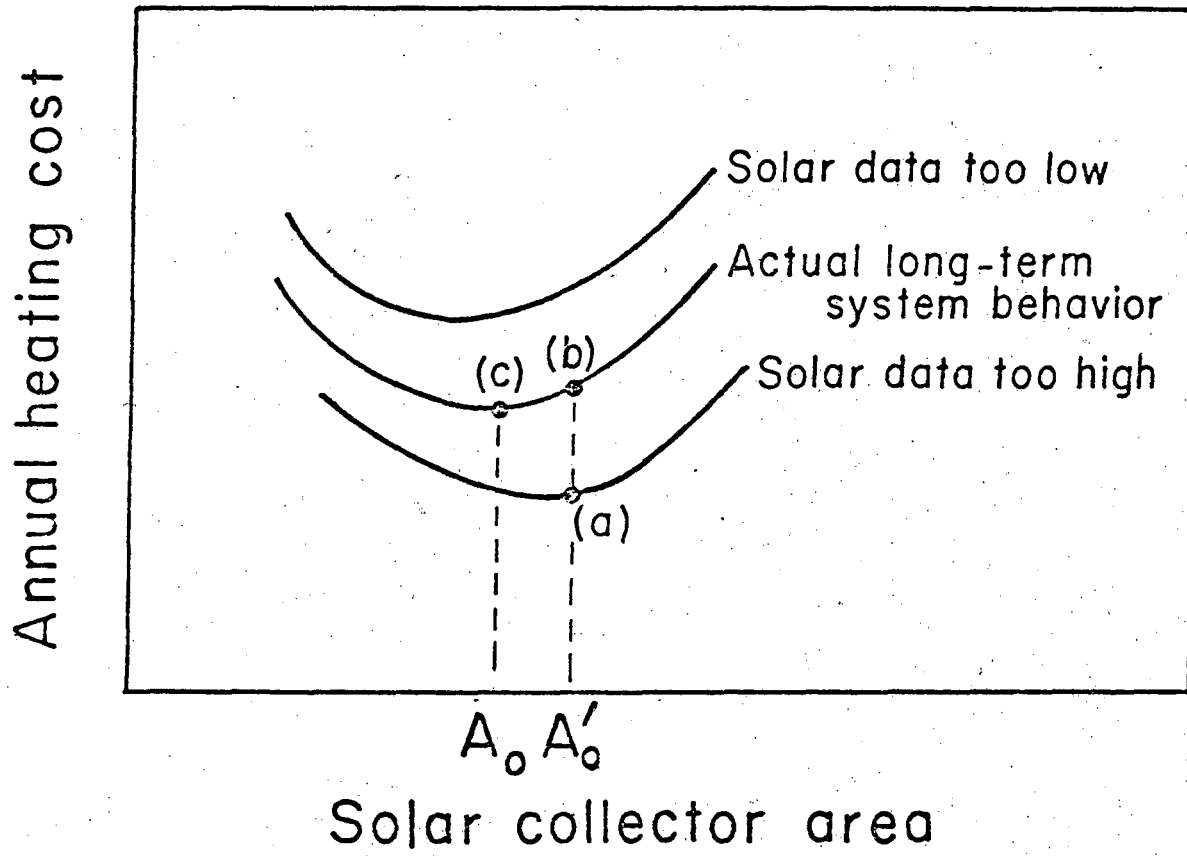
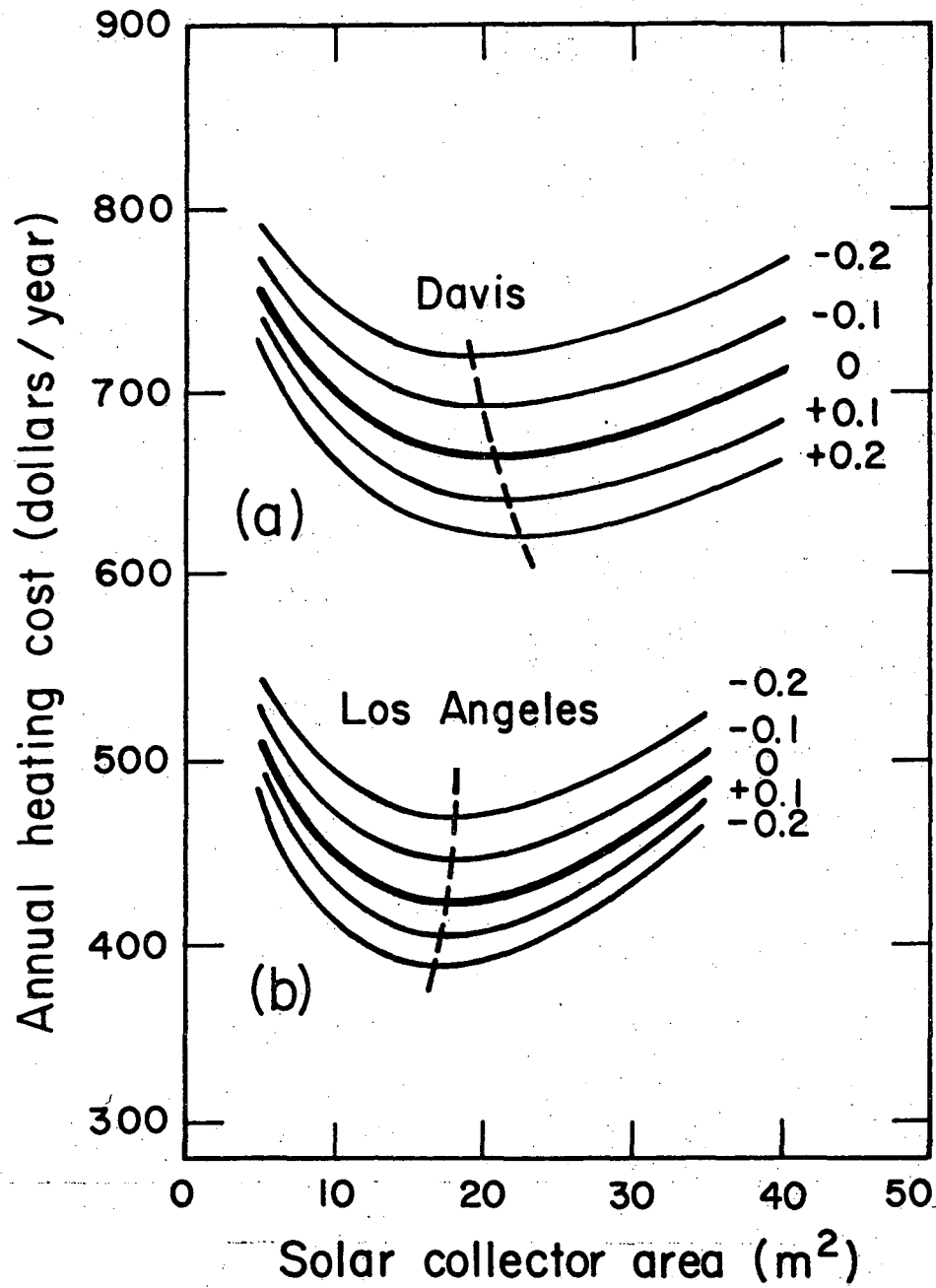


Fig. 5



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Fig. 6

This report was done with support from the United States Energy Research and Development Administration. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the United States Energy Research and Development Administration.

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