Dynamic Modeling and Sensitivity Analysis of Solar Thermal Energy Conversion Systems

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Since the energy input to solar thermal conversion systems is both time variant and probabilistic, it is unlikely that simple steady-state methods for estimating lifetime performance will provide satisfactory results. The work described here uses dynamic modeling to begin identifying what must be known about input radiation and system dynamic characteristics to estimate performance reliably. Daily operation of two conceptual solar energy systems was simulated under varying operating strategies with time-dependent radiation intensity ranging from smooth input of several magnitudes to input of constant total energy whose intensity oscillated with periods from 1/4 hour to 6 hours. Integrated daily system output and efficiency were functions of both level and dynamic characteristics of insolation. Sensitivity of output to changes in total input was greater than one. These findings support the feeling that interplay of radiation dynamics and collector response times affects the quality of energy delivered, and therefore system performance.

I. Introduction

Considerable effort is currently devoted to development and demonstration of concepts for utilizing solar energy, anticipating an eventual significant contribution from that source to meeting society's energy needs. Widespread implementation of solar conversion systems, particularly those for production of solar thermal power, will not occur, however, until they can be designed to meet cost and performance specifications with reasonable assurance. There are intrinsic differences between solar-driven power systems and those the engineering community has traditionally dealt with. Conventional systems can be designed for predominantly steady-state operation at the appropriate capacity, then provided with the amount of fuel necessary to produce the output expected. Design of a solar power system, in contrast, must be done not only on the basis of its intended output but also considering the energy input that can be expected during its lifetime. That energy input is location-dependent and time-variant; fluctuation of solar radiation intensity with time is only partly deterministic, with largely probabilistic effects occurring on time scales from minutes to seasons or longer.

One consequence of these characteristics is that solar-driven power systems must spend a significant portion of their operating time responding to input transients. Another consequence is that a long lead time is required to evaluate the solar resource at any one location. This paper addresses the thesis that performance analysis for solar thermal power systems must take into account the dynamic characteristics of both the

components and the input energy to lead to satisfactory results. There is a need to identify in a fundamental sense what aspects of system dynamic response are important to performance under what conditions. Among other things, this understanding would allow timely initiation of insolation measurement programs that would yield without excess expense information adequate to support reliable design of commercial solar power systems.

The work described here represents an initial sensitivity analysis whose goal was to determine how a solar thermal conversion system's output responds to variations in the energy input. One objective was to learn how much performance estimates might be affected by uncertainty in the magnitude of measured insolation values. Another was to gain some understanding of what effect variations in solar radiation intensity on several time scales (cloudy skies) might have on system performance, and how any such effects might depend on those system parameters that govern its dynamic response characteristics.

II. Description of the Study

Since fundamental understanding was sought here, rather than detailed analysis of any specific systems, a generalized approach to the problem was taken. Emphasis is on dynamic behavior, and we wish to examine interactions one step at a time. System behavior is considered here in terms of energy flow, starting with solar radiation intensity as a time-dependent input. The model system is envisioned as the simplest group of components that will take that input as heat and convert it to mechanical energy, the output. A computer-based dynamic model serves to relate mechanical energy production to radiation input as a function of time and the system's dynamic characteristics. Calculation of the energy outputs resulting from a representative set of driving functions yields data from which judgment can be made regarding the sensitivities we are interested in.

A. Dynamic Modeling Technique and Model System

The dynamic model used in this work represents a simplified application of a versatile methodology for time-dependent simulation of the energy transfer behavior of systems and their components (Ref. 1). The technique has been applied at various levels of detail, from rough examination of system behavior in response to general specifications on subsystem performances (Ref. 2) to detailed analysis of effects exerted on a component's transient and integrated performance by its thermal characteristics (Ref. 3). Functionally, the model performs an explicit forward finite difference analysis on energy flow in a system, which may be defined as made up of a collection of components or subsystems, or of segments of one component. It is expressed in a framework that retains an intuitively understandable connection between parameters and their effects and is embodied in an interactive computer program of modular design for flexibility in adding or substituting a variety of components.

For purposes of this study, the system illustrated in the energy flow diagram, Fig. 1, was characterized for simulation. Representation of the solar collector is quite general; it is treated as a lumped energy transfer device. The parameters used to model the collector include: thermal capacitance (the aggregate heat capacity of those portions of the component in which energy will accumulate, like absorber structure and heat transfer fluid); a lumped heat loss coefficient (which need not be constant, but can be expressed as a function of collector temperature or internal energy); and characteristics of the heat transfer fluid (specific heat, flow rate, temperature at collector inlet—these also need not be constant). These descriptive parameters are all expressed as values per unit area of collector aperture, allowing treatment in the model of collectors with widely varying shapes, sizes and concentration ratios. An ideal engine operating at a fixed fraction of Carnot efficiency is assumed for conversion of the collected thermal energy to mechanical energy. Pertinent characteristics of the surroundings are ambient temperature and a sink temperature to which the Carnot engine rejects heat.

A simulation begins with an initial value for the internal energy content of the collector and proceeds according to the equation

$$CHS_{(T+DT)} = CHS_{(T)} + (CHIR_{(T)} - CHOR_{(T)})DT$$

in time steps that are small in comparison with both system response times and rate of change of radiation intensity.

CHS designates the heat stored in the collector at the time subscripted, *CHIR* is the net rate at which energy enters the collector, *CHOR* is the net rate for energy leaving the collector and *DT* is the time increment over which the rates apply. Both rates are determined for each time step from solar input rate, the collector parameters, and parameters describing the surroundings (in this case ambient temperature) pertaining at time *T*. At each time step, the temperature of fluid leaving the collector (on which engine efficiency will depend) can be determined from the corresponding value of *CHS*. Here it was assumed for simplicity that the temperature distribution between collector inlet and outlet is linear and the temperature defined in terms of *CHS* corresponds to the average between the two. Finer spatial resolution could be used, but would not affect qualitatively the findings produced.

As written, the computer code contains one set of characteristic system parameters and initial values. To run the program, inputs are provided in the form of an equation describing solar radiation intensity as a function of time plus any desired changes in the descriptive parameters. Simulation corresponding to one working day (12 hours from sunup to sunset) is carried out in each run; program outputs include solar radiation input integrated over the day, converter output integrated over that period, and integrated system efficiency (total output/total input) for the day.

B. Protocol for Parameter Variations

Our experimental system was first characterized in a baseline configuration, whose specifications are summarized in Table 1. The first five entries represent quantities that remained constant throughout this study. Those in the lower group comprise the collector-dependent parameters and operational characteristics that it was anticipated would affect system dynamic response. Each of these factors was varied in the course of the investigation.

While the system we are looking at is an admitted abstraction, the parameters used to describe it are not chosen entirely arbitrarily. Specifically, the values of collector thermal capacitance and heat loss coefficient used are consistent with the characteristics of existing collectors. The parameters incorporated into the baseline configuration correspond to a glass concentric tube collector produced by Owens-Illinois; they are derived from a separate detailed dynamic analysis of that collector. The concentric tube design is characterized by large thermal inertia and slow response. For an alternate set of collector parameters, thermal capacitance and loss coefficient values representing a fast responding collector, a NASA-Honeywell design, were also tested. Those were experimental values (Ref. 4). Both choices are examples of moderate performance, non-concentrating collectors.

Six variations on the baseline configuration were examined. For each of the two collector types (slow responding and fast responding) system performance was simulated under three different sets of hypothetical operating constraints. Two of those involved operation with collector heat transfer fluid flowing at a constant rate (chosen for each collector such that a steady solar input of 1 kW/m^2 would produce an equilibrium outlet temperature of 240°C). In the first constant flow rate case, the engine was programmed to accept all the energy delivered to it above 62°C, the inlet temperature, for conversion. A somewhat more realistic second case limited the engine to utilizing only energy above 100°C. The third set of operating constraints involved variation of the fluid flow rate to maintain the collector outlet temperature within a fairly narrow range (175-200°C).

Daily performance for each modification of the baseline configuration was simulated using a systematically varied set of solar radiation inputs. Those included a basic "clear-day" function (the first loop of a sine function plus some third harmonic, Fig. 2) with amplitudes of 1, 0.8, 0.6, 0.4, and 0.3 or 0.2, intended to mimic days ranging from clear to uniformly hazy. To examine the effect of oscillations in radiation intensity, sine functions of amplitude 0.4 were imposed as a harmonic component on the basic function with amplitude 0.6; the periods of those harmonics varied from six hours down to 15 minutes. Figure 3 illustrates a sample of harmonic input.

III. Results

Figures 4 and 5 summarize the effects exerted on performance of our conceptual systems by their dynamic characteristics and operating strategies, in response to solar input containing only smooth diurnal variation. Integrated daily system efficiencies are plotted against integrated daily insolation; it can be seen that in all cases tested integrated efficiency is a non-linear function of total energy collected. This is a consequence of the fact that a heat engine's performance depends on both the quantity and quality (temperature) of the energy delivered to it, and reflects the impact of radiation intensity on the temperature increase that can be sustained in the collector heat transfer fluid.

Data from these runs were used to determine the sensitivity of system output estimates to uncertainty in the knowledge of total input. Plots of total output versus total input were constructed, and the range of system outputs corresponding to a variation of ± 10% and ± 15% around a nominal daily radiation input of 7 kWh/m^2 was extracted. The resulting sensitivities, expressed in terms of percentage output change divided by percentage change in input, are tabulated in Table 2. Owing to the non-linearity of the input-output curves the sensitivity values vary some, but all are 1.6 or greater. They indicate that a 10% inaccuracy in a measured value of daily insolation would lead to an estimate of system performance for that day that would be in error by at least 16%, even if the performance estimate were based on dynamic analysis.

The results discussed above apply to operation of two imaginary non-concentrating solar thermal energy conversion systems on days ranging from uniformly hazy to uniformly clear. Figures 6 and 7 show the effect on system performance of some short-term variations in radiation intensity, mimicking cloud passage in otherwise clear skies. In these graphs all points represent response to the same total radiation input, 5.38 kWh/m^2. The variables represented are operating strategy and the period of oscillation for the superimposed harmonic in

the solar radiation function. Deviations in system efficiency from that produced by smooth input were plotted against the harmonic period. Here the influence of collector response time shows strongly. Performance of the system containing a fast-responding collector is more sensitive to the frequency of input transients, but both collectors produce the same general behavior. System efficiency is higher than expected from the total daily input when radiation intensity oscillates slowly compared to the collector's response time—the system can develop higher working temperatures when it has time to respond to the peaks in intensity. Conversely, intensity oscillations that are too rapid to follow tend to degrade system performance, since the collector cannot take advantage of the peaks to make up for energy missed during the troughs. In the case of the fast collector, system efficiency varies nearly ± 15% from that seen with smooth input as the dynamics of input radiation change.

IV. Conclusions

In all the cases examined in this study, both the integrated daily system output and system efficiency as estimated by dynamic simulation were functions of both the level and dynamic characteristics of the insolation that was assumed to drive the system. System output showed a sensitivity of significantly greater than one to variations in the magnitude of total radiation assumed, even without considering the additional effects produced by input transients. These findings support the intuitive feeling that the interplay of input radiation dynamics and collector response times can have a pronounced effect on the quality of energy delivered, and therefore on system performance. They also suggest that evaluation of system performance for design purposes must be based on accurate radiation figures, either measured data or a modeled equivalent, spaced at short time intervals. Most of the insolation data currently available or reconstructable is likely to be neither accurate enough nor detailed enough to support design of a commercial solar power plant (Ref. 5).

The effects observed here apply to an abstracted, highly simplified system concept. More work is needed to probe, systematically, other factors that have potential for affecting the dynamics of system performance. Realistic engine performance characteristics should be included, as well as the effects of storage subsystems. The ultimate goal is an understanding of which design parameters tend to exaggerate and which tend to attenuate the basic input-output sensitivities demonstrated here. With that understanding should come ability to design solar power systems for efficient performance at their designated sites, and to specify the requirements on insolation data necessary to support site selection and design.

References

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Table 1. Specifications for system baseline configuration

Parameters held constant	
Heat engine mechanical/cycle efficiency	0.8
Sink temperature	35°C
Ambient temperature	25°C
Heat transfer fluid specific heat	$9.99 \times 10^{-4} \frac{\text{kWh}}{\text{kg}^\circ\text{C}}$
Collector inlet temperature	62°C
Variable parameters	
Collector thermal capacitance[a]	$0.016 \frac{\text{kWh}}{\text{m}^2{}^\circ\text{C}}$
Collector heat loss coefficient[a]	Variable[b]
Heat transfer fluid flow rate	$4.5 \frac{\text{kg}}{\text{hm}^2}$
Temperature of energy accepted by converter	>62°C

[a]For alternate collector, thermal capacitance is 0.0026 kWh/m^2°C, loss coefficient is 26.8×10^{-4} kW/m^2°C.

[b]Varies with collector temperature from 8.7×10^{-4} kW/m^2°C at 62°C or less to 15.9×10^{-4} kW/m^2°C at 102°C or greater.

Table 2. Sensitivity measures for system response to smooth radiation input of nominal 7 kWh/m^2

$\frac{\Delta I}{I}$	$\left(S = \frac{\Delta O/O}{\Delta I/I}\right)$ Fast collector: Constant flow	Fast collector: Constant temperature	Slow collector: Constant flow	Slow collector: Constant temperature
- 0.10	1.65	1.9	1.62	1.7
+ 0.10	1.74	1.62	1.69	1.61
- 0.15	1.71	1.78	1.69	1.64
+ 0.15	1.71	1.65	1.64	1.64

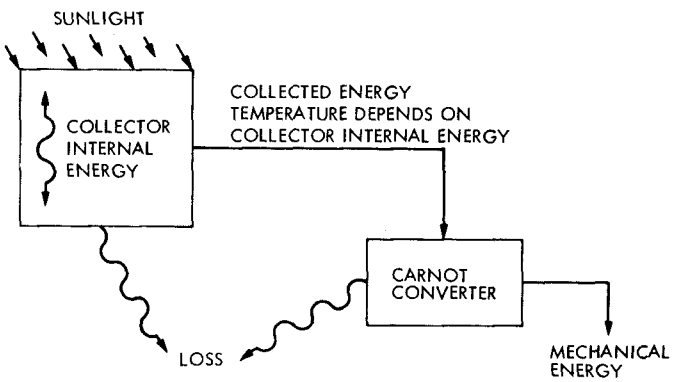

Fig. 1. Abstracted system for sensitivity analysis, diagrammed in terms of energy flow

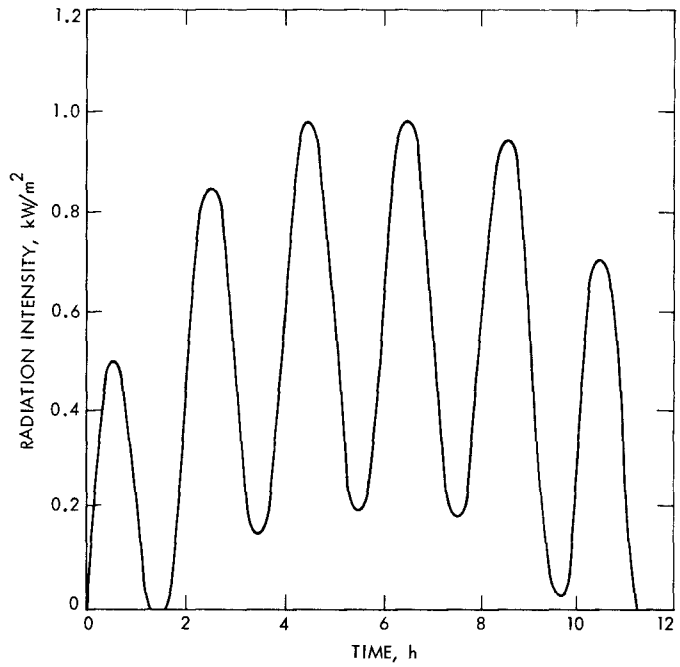

Fig. 3. Sample of input function with superimposed harmonic of 2-hour period

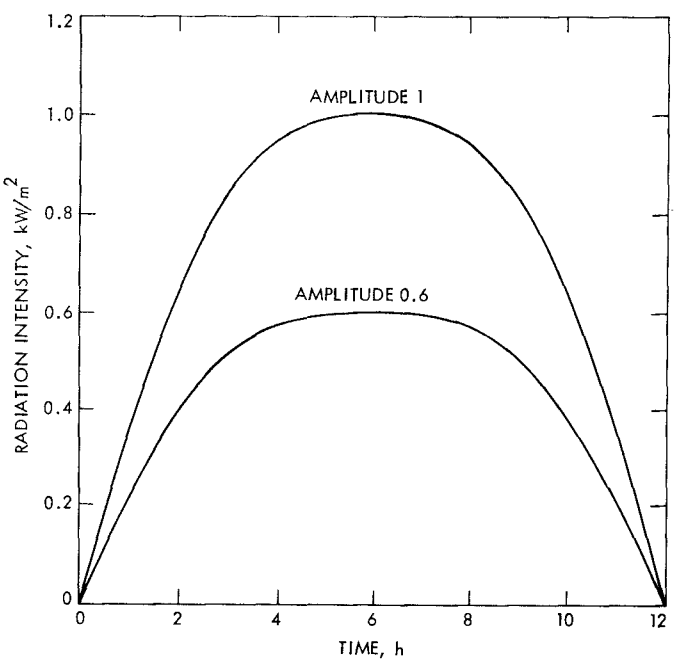

Fig. 2. Basic smooth input function for solar radiation intensity

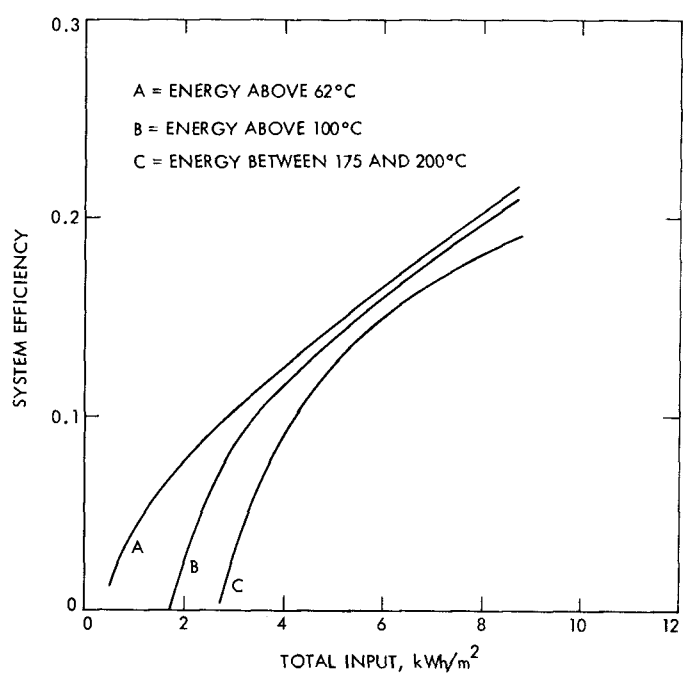

Fig. 4. Integrated system efficiency versus smooth daily radiation input for system containing slow responding collector

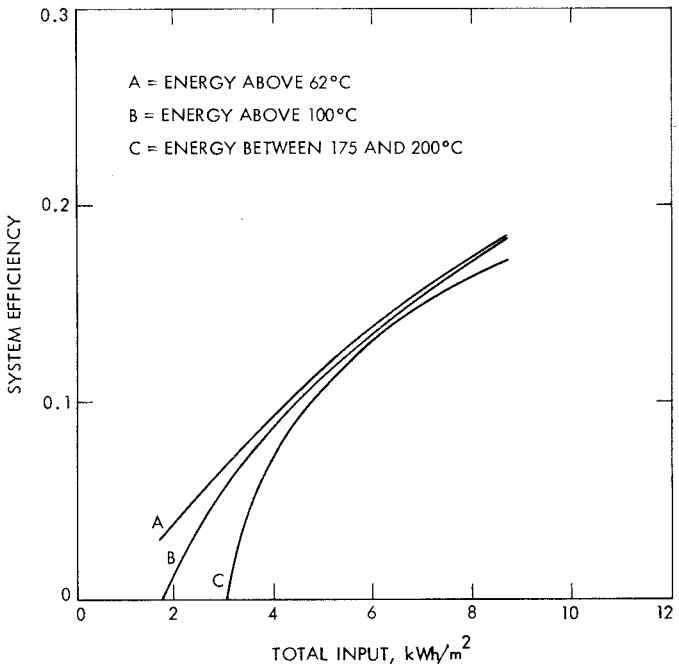

Fig. 5. Integrated system efficiency versus daily radiation input for system containing fast responding collector, smoothly varying input curve

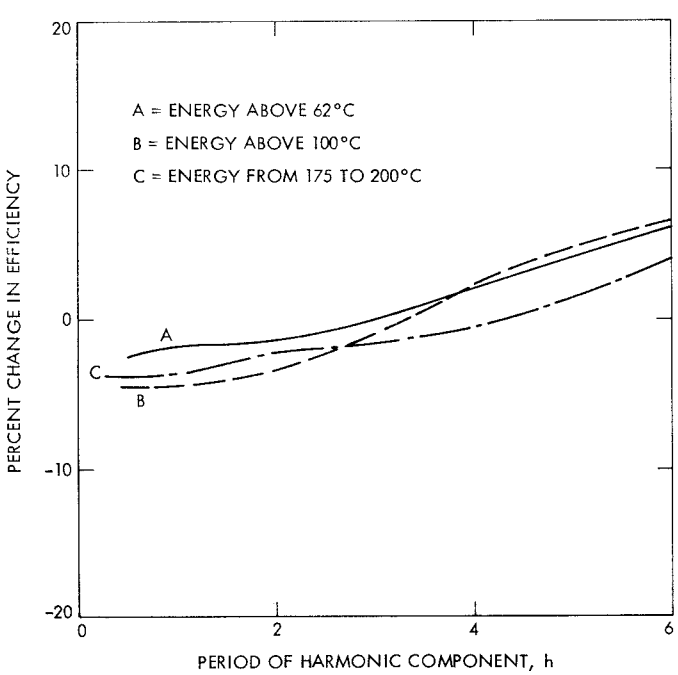

Fig. 6. Effect of input transients on efficiency of system with slow collector

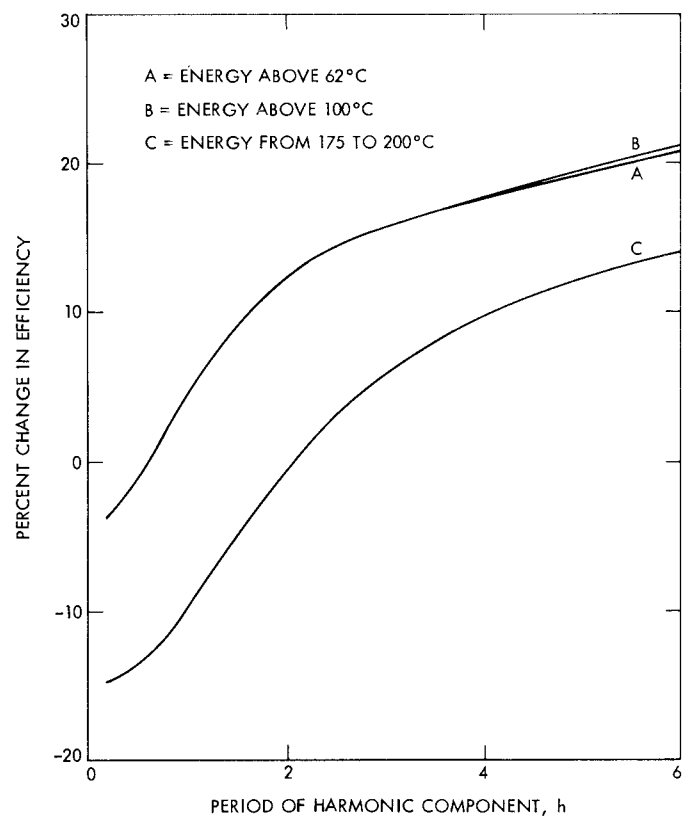

Fig. 7. Effect of input transients on efficiency of system with fast collector

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