An Experiment in Dynamic Modeling for a Complete Solar-Powered Energy System

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Completion of a prototype dynamic model simulating the performance of a solar-powered energy system is described. A set of hypothetical components is specified, and the outcome of test analyses of the resulting system is outlined. On the basis of this exercise, it appears that the dynamic modeling technique will constitute a useful and convenient tool for analyzing performance of time-dependent systems.

I. Introduction

A previous report (Ref. 1) has described in general terms a technique under development to model the time-dependent performance of solar-powered energy systems. In that article, a hypothetical system intended to provide all the energy needed by the Goldstone Space Communications Complex was outlined. Two of the three computer programs needed to embody the model of that system were discussed. The third program has been finished, and some experimental runs have been made to examine the modeled performance of the entire system.

The Goldstone Energy Conservation Project is no longer directed toward development of a full energy system for the Complex. For that reason the whole-system model has not been refined past the prototype stage, and the representative programs (SUN, WIND, and SENSMOD2) are implemented without the range of user options that would be included in a fully operational version. Construction and manipulation of the prototype have constituted a useful and informative experiment that has contributed to the definition of systematic processes for creating dynamic system models. This report will summarize the completion of the prototype model and results of the exploratory performance analyses that were carried out with it.

II. Characterization of the Test System

In Ref. 1 the components of a hypothetical baseline energy system were identified, and information flow between the computational modules representing them was outlined. These are illustrated in Figs. 1 and 2. Before the model can be used to carry out a performance analysis, key characteristics of each component must be specified. A component's key characteristics are those parameters which are needed in the corresponding computational module to calculate the outgoing information from the incoming information. In general, characterization can be carried on at several levels of detail, depending on information available and the goals of the analysis. A heat engine, for example, can be specified simply in terms of size and overall efficiency for purposes of, say, a quick-scan evaluation. If more precise system analysis is desired, the specification can be made more detailed, including variation of efficiency with working fluid and rejection temperatures. Even a complete step-by-step calculation of cycle performance, treating the engine as a subsystem in itself, may be incorporated if desired.

The following paragraphs contain a listing of key characteristics for the hypothetical system components put together for the purpose of exercising the dynamic model. Note that these are gross component characteristics derived from a first guess at some performance specifications that would be required to make a whole energy system that is economically feasible. They do not necessarily correspond to physical characteristics of actual existing or emerging components. Analysis at this level corresponds to examination of a system's operation in terms of subsystem design goals.

A. Solar Subsystem

Program SUN, described in Ref. 1, embodies the model of a subsystem consisting of solar collectors, heat storage, and a heat engine for generation of electricity.

For purposes of exploratory analysis, 200,000 m^2 of fixed flat collectors made mostly of glass were postulated. They were assumed to face south, tipped up at 35.4 degrees from horizontal. Heat loss rate was taken to be about 350 watts per square meter at a collector temperature 300°C above ambient; loss was assumed to be predominantly radiative. An organic fluid was specified for heat removal. The fluid flow rate was controlled to maintain the outlet temperature between 300°C and 340°C (flow was stopped if the fluid temperature was below 300°C). Acceptance of incident radiation was assumed to decrease drastically at angles of incidence greater than about 50 degrees from normal.

Heat storage was accomplished with a set of narrow tanks holding a total of 3.8×10^6 kg of the organic fluid. The tanks were assumed to be well enough insulated so that heat loss from them was negligible over the time span of a few days. Fluid in them was assumed stratified into two well-defined zones. Immersed in each tank was a heat transfer tube through which the heat engine working fluid was circulated. Flow to the engine was maintained at a constant rate as long as enough heat remained in the high-temperature zone to last through the next integration interval. When there was insufficient heat stored at the high temperature (roughly 300°C to 340°C), fluid flow to the engine was stopped. The total storage unit was sized to hold one day's output from the collectors under conditions of maximum insolation, estimated on the basis of annual average figures.

A Rankine cycle engine was included to generate the DC output from the solar subsystem. It was to use the same organic liquid as its working fluid. It was postulated to run at 90% of Carnot efficiency with a mechanical efficiency of 80% and generating efficiency of 90%. Total fluid flow to the engine was set at 14,200 kg/h, estimated to use up in a 24-hour period the whole output of the collectors on a day with maximum insolation.

B. Wind Subsystem

WIND is the program used to simulate the performance of a wind-driven generator. Wind turbine output was taken as proportional to the cube of wind speed whenever that fell between 8 and 32 km/h. No generation occurred when wind speed was outside that range. Maximum output rate (at 32 km/h) was 4000 kW.

C. Conversion and Storage Subsystem, SENSMOD2

Using the outputs from SUN and WIND, SENSMOD2 models the remainder of the energy system, including hydrogen generation and storage, direct DC to AC conversion, dual-fuel engine generators, load consisting of waste heat utilization and electrical demand, and the chosen dispatch strategy. Characterization of the components represented by SENSMOD2 was done in very basic terms. Efficiency of the electrolysis unit was set at 80%. A maximum capacity for hydrogen storage was not defined; the amount of hydrogen in storage was monitored, and the gas was defined to be available for use long as enough remained to satisfy the next hour's demand. The engine-generator was specified to be 33% efficient using either hydrogen or diesel fuel. DC to AC conversion was assumed to proceed at 85% efficiency using a converter with 1250-kW capacity. Diesel fuel in storage was monitored, and whenever the amount there fell below 2,000,000 kWh a "load" of 200,000 kWh was added to it. A base waste heat load of 600 kW that varied ±10% with ambient temperature was postulated. Electrical load was approximated very simply, using a cumulative density function that was linear between a base defined as half the average load and a peak defined as 1.5 times average load.

For the prototype Dispatch Module the following strategy was devised. All power from the wind turbine was used for electrolysis. Power from the solar subsystem was routed through the DC to AC converter to the extent that it was required and available; any solar power not used directly was consumed by the electrolysis unit. The engine-generators were required to operate to meet waste heat demand, producing an equivalent base amount of electricity. Electrical demand above that base was met with direct power from the converter to the extent it was available, up to converter capacity. Demand exceeding that level was to be satisfied by additional engine-generator operation. Hydrogen would be used to fuel the generators as long as there was enough; then the engines would switch to operation on diesel fuel.

SENSMOD2 is a program analogous in design to SUN and WIND. None of the components of the conversion-storage subsystem required modeling with variable step size integration, and the simulation could be run with update at hourly intervals. While SENSMOD2 was being put together, a requirement for ordering computational modules in the program was discovered. The relationships simulating the hydrogen-oxygen subsystem, the engine-generator, and fuel storage all occur in the DOWNSTREAM subprogram, and each of those computational modules requires information from one of the other two. Thus the Hydrogen-Oxygen, Engine-Generator, and Fuel Storage Modules had to appear in the appropriate sequence in the program. This ordering requirement places some restriction on flexibility in manipulating the system model as embodied in the program, as it represents one more piece of information not related to the system under analysis that the user has to remember. It may be that more skillful design of the Dispatch Module will avoid this drawback in future efforts.

The computational module representing the dispatch function differs from those described in Ref. 1. A "normal" computational module contains relationships defining component performance. Those relationships with no need for information from other computational modules (components) are contained in the UPSTREAM subprogram, while the equations using parameters transferred from another module appear in subprogram DOWNSTREAM. Between the two, CROSS-COUPLE carries out the transfer of variables from module to module. While the Dispatch computational module is made up of a relatively complex set of logical operations, its real function remains one of transferring information. The pieces of information have been manipulated before transfer, but not used to calculate new variables. Thus the Dispatch Module belongs strictly in the CROSS-COUPLE subprogram.

III. Performance of the Test System

To test the performance of the model and programs, operation of the hypothetical system summarized above was simulated over the course of one month, January. For input to SUN, a table of hourly insolation values was generated using the ASHRAE model (Ref. 2) with clearness number 1.05; each day's values were modified by a probabilistically determined factor to include the effect of unclear days. Ambient temperature inputs were from a file containing a composite of experimental hourly values measured at Goldstone over about three years. Wind speed inputs to WIND were drawn from a cumulative distribution based on three years' measurements at Goldstone. Output from SUN and WIND was stored as hourly average values for input into SENSMOD2, which also used the ambient temperature file.

A run of SENSMOD2 was made, simulating the system as specified. Several measures of system performance were output, among them the amount of hydrogen in storage at the end of each day and daily totals for solar-generated electricity, wind-generated electricity, hydrogen consumed, and diesel fuel consumed. Production of electricity from wind turned out to be a small fraction of the output from the test system (less than 10%). Figure 3 summarizes the salient features of system operation for the month of January. The top line represents daily totals for heat gathered by the solar collectors; it was generated by program SUN. Solar subsystem daily total production of electricity varied between 58,500 and 198,000 kWh. Hydrogen in storage, starting from an initial value of 200,000 kWh, decreased rapidly while consumption of diesel fuel (graphed as a cumulative value) rose to a total of over 640,000 kWh by month's end.

Inclusion of waste heat utilization in the system required that the engine-generators run all the time to meet that demand, consuming a great deal of hydrogen in the process. Direct use of the solar-generated electricity would seem to offer a significantly more efficient strategy. As a first parameter variation, then, the provision for waste heat utilization was removed, electrical demand was increased to compensate, and the capacity of the DC to AC converter was doubled to 2500 kW. Figure 4 shows the effect of these changes on cumulative diesel demand and hydrogen storage level (heat collected and solar subsystem output remain unchanged). Contrary to expectations, lifting the requirement for compulsary base operation of the generators did not lower diesel consumption (which is the measure of overall system performance chosen here) but rather increased it substantially.

Examination of the hourly electrical output from the solar subsystem revealed that the heat engine there exhausted the heat in storage in an average of 14 hours, and there was no solar power production the rest of the day. In an effort to better match power generation with the load distribution, which was spread over all hours, the output rate of the heat engine in the solar subsystem was decreased by halving the flow rate of working fluid to the engine (from 14,200 to 7100 kg/h). SUN was re-run with that modification, and the resulting data input for a third run of SENSMOD2. Hydrogen accumulation and fuel demand observed under these conditions are plotted in Fig. 5. This last modification significantly reduced diesel fuel consumption.

IV. Summary

A dynamic model simulating the performance of a complete energy system has been formulated and embodied in a set of computer programs. Those programs are functionally complete but do not contain all the features providing user convenience that would be present in fully implemented versions. Characteristic parameters were specified for a set of hypothetical components, and the programs were used to carry out some exploratory analyses of the resulting system. Parameter variations reflecting system and component modifications were easily and quickly made. The test runs described provided considerable insight into the behavior of a fairly complex solar-powered system and allowed rapid refinement of the system leading to improved performance (by one measure at least).

Additional work in dynamic modeling involves a program that produces instantaneous and integrated performance measures for solar collectors alone, using experimentally measured solar radiation inputs at short time intervals. Collector characterization packages are undergoing continual refinement. Also in progress is a detailed analysis of a solar heating and cooling system to be designed using commercially available components.

References

1. Hamilton, C. L., "A Dynamic Model for Analysis of Solar Energy Systems," in *The Deep Space Network Progress Report 42-27*, pp. 41–51, Jet Propulsion Laboratory, Pasadena, Calif., June 15, 1975.
2. *ASHRAE Handbook of Fundamentals*, Chapter 22, pp. 386–394, American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, N. Y., 1972.

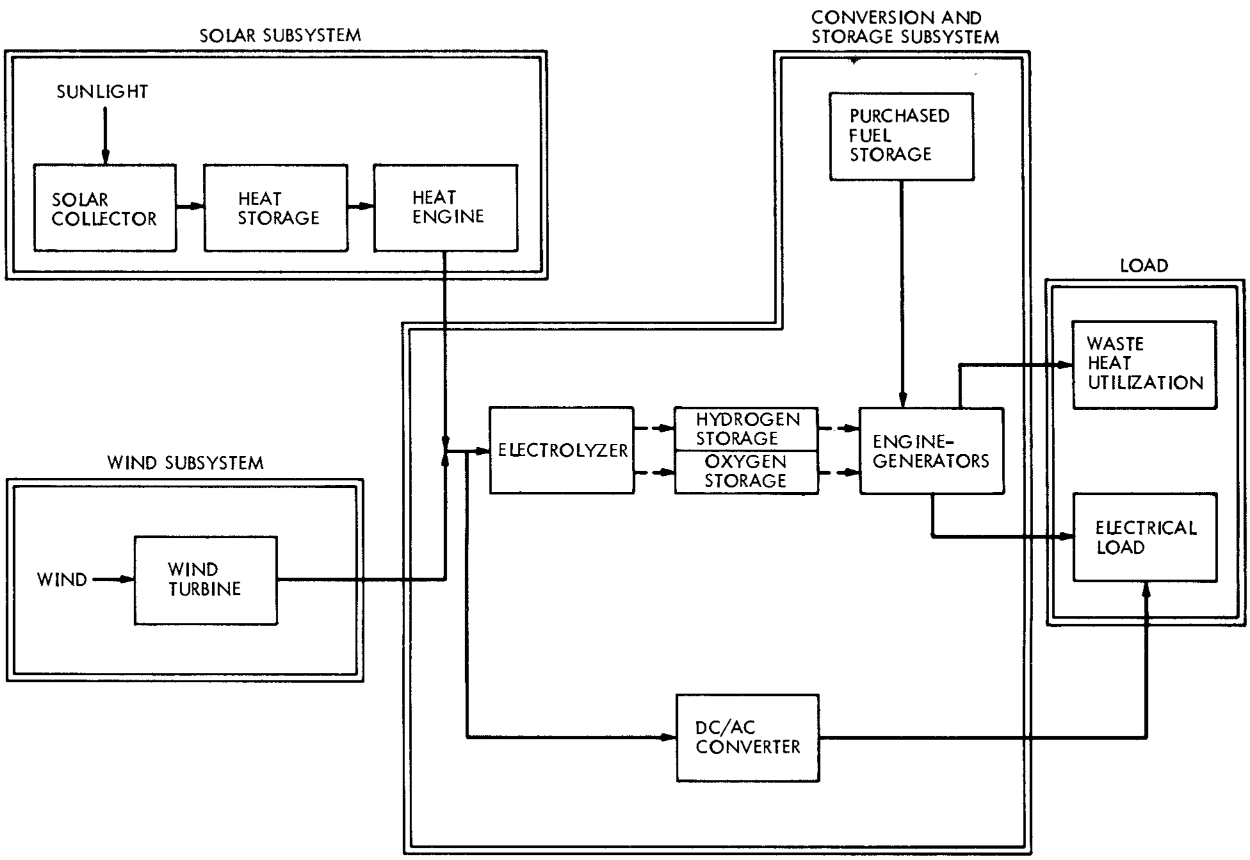

Fig. 1. Hypothetical solar energy system used in tests of model

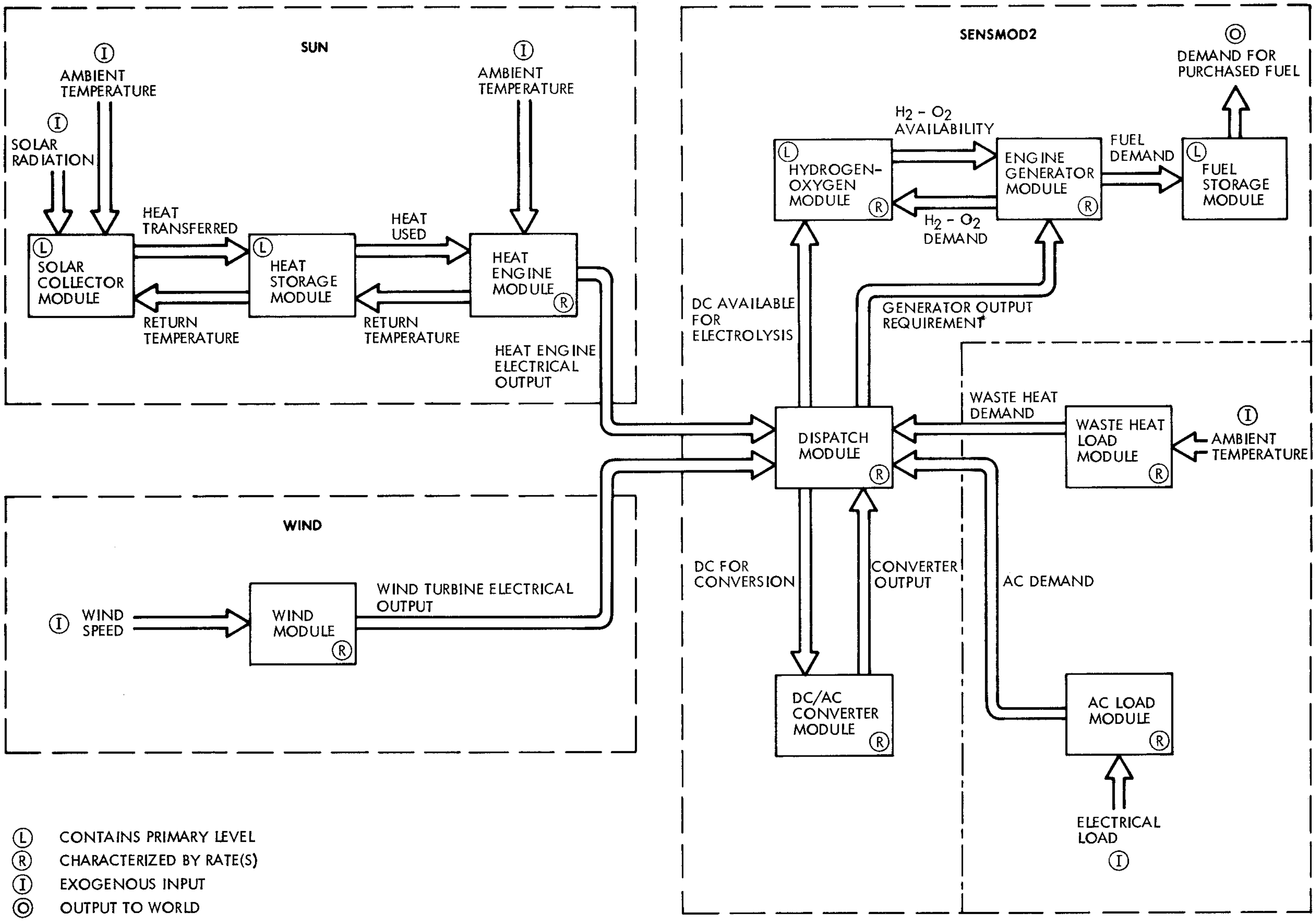

Fig. 2. Computational modules and data flow for hypothetical system

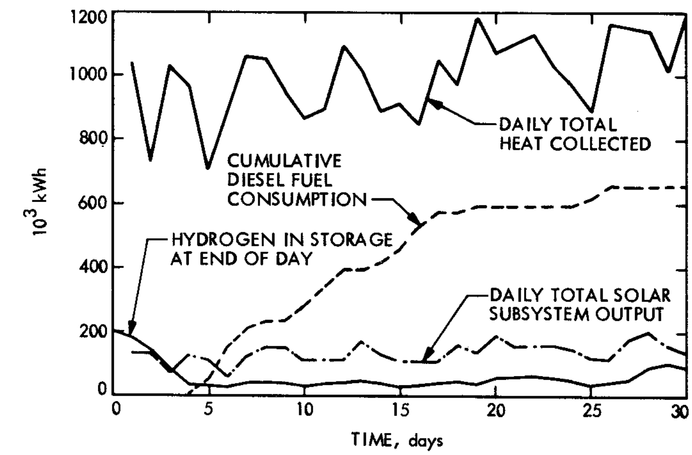

Fig. 3. Performance of hypothetical system as specified

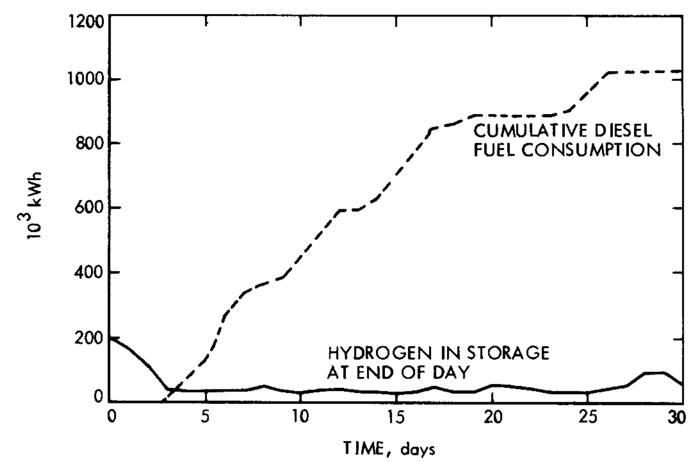

Fig. 4. Performance of hypothetical system without waste heat utilization

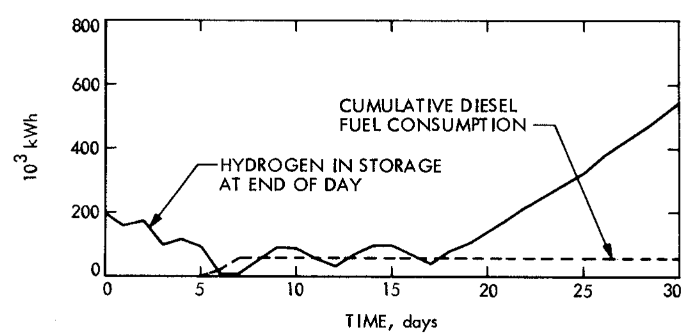

Fig. 5. Performance of hypothetical system without waste heat utilization after heat engine rating cut in half