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PHOTOVOLTAIC MISSION ANALYSIS:
PROGRAM SUMMARY REPORT FOR PERIOD
FROM 15 AUGUST 1978 TO 28 FEBRUARY 1979

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I. INTRODUCTION

The work described in this Program Summary Report was performed under DOE (originally ERDA) Contract EY-76-C-03-1101, Project Agreement 8, Modification 5, during the period between 15 August 1978 and 28 February 1979. It represents the latest installment of the ongoing effort covered by Project Agreement 8, which went into effect in December 1975.

The overall objective of the project since its inception has been to support the planning, development, and guidance of the DOE National Photovoltaic Program on a continuing basis by: (1) identifying and evaluating those photovoltaic applications (including total energy applications) that are most likely to lead to significant contributions to the national energy supply, (2) identifying and evaluating attractive opportunities for demonstration programs and other strategies (e.g. tax incentives) that will stimulate the growth of the near-term (1986-2000) photovoltaic markets, and (3) providing technical support to the DOE Photovoltaic Program Office.

In pursuit of this general goal, the Aerospace Corporation has provided direct technical and management support to the ERDA and DOE Managers of the National Photovoltaic Program on a continuing basis and has, in addition, carried out a wide variety of studies and analyses (Refs. 1-8).

The work reported here is a direct extension and outgrowth of these earlier studies. It includes analytical studies in two areas and a continuation of the program support activities that have been a part of the project since its inception. Section II of this report contains a summary account of the first of these studies, a preliminary examination of the technical and cost impact on utility distribution systems of the introduction of grid-connected residential photovoltaic systems that feed back excess photovoltaic electricity into the utility grid. This work is also described in greater detail in a separate topical report (Ref. 9).

The second study, discussed in Section III, was a technical and economic evaluation of a novel photovoltaic power plant concept, a hybrid

high-concentration system in which thermal energy removed in cooling the photovoltaic cells is used to generate additional electricity in a bottoming-cycle turbine. An earlier and very preliminary analysis (Ref. 1) had indicated that this concept is a promising one, and a start had already been made (Ref. 8) on the development of a computer program to permit detailed simulation of the operation of such a system and thus a more complete evaluation of its potential. During the current report period, this program was completed, checked out, and used in an initial evaluation of the performance of the system and the cost of its operation. A more detailed discussion of this work is presented in a separate topical report (Ref. 10).

The final section of this report, Section IV, summarizes the program support services that have been performed during the report period.

II. THE IMPACT ON UTILITY DISTRIBUTION SYSTEMS OF ON-SITE RESIDENTIAL PHOTOVOLTAIC POWER GENERATION WITH FEEDBACK TO THE GRID

Several recent studies (e.g., Refs. 6, 11) have indicated that the use of roof-mounted photovoltaic generators to serve the electric power demand of single-family residences is perhaps the most promising large-scale terrestrial application for this solar energy conversion technology. The preferred configuration appears to be one in which the photovoltaic system (including electric storage capacity, if any) is so designed that a significant fraction, but not all, of the required energy is of solar origin, with the remainder provided by the conventional utility grid.

The existence of the connection to the grid, i.e. to utility power distribution systems, introduces the possibility of feeding back excess photovoltaic electricity (generated, for example, when the residence demand is low during a period of high insolation) into the grid for use by other customers. The economic attractiveness of the residential photovoltaic application would be considerably enhanced if such feedback took place and the owner of the photovoltaic system received some form of remuneration for the energy provided. The question of how to pay the photovoltaic system owner for this energy, and how much, is a complicated one that has not been studied in detail. It is, however, clear that before this question can be answered, it will be necessary to determine how much it would cost the utility to accept the feedback power, i.e. to identify the changes that would have to be made in utility equipment or procedures and to compute the economic impact of those changes. It is to this latter issue that the study report in this section is addressed.

1. Study Objective and Scope

The objective of this study has been to make a preliminary but quantitative assessment of the technical and cost impacts on utility distribution systems resulting from the feedback of power into the grid from on-site residential photovoltaic systems. It was assumed that the photovoltaic systems were intended, and designed, primarily to serve the

electric loads of the homes on which they were located. It was further assumed that any power generated in excess of these requirements would be fed back into the utility distribution grid to serve other loads.

Because of the limitations in available time and resources, it was necessary to restrict the scope of the investigation in several respects. As is indicated above, only residential loads and residential photovoltaic systems were considered. Further, only one distribution system configuration was represented in the analysis, and the assumption was made that all photovoltaic feedback power was expended within the confines of the basic local unit of the utility distribution system (i.e. no power feedback through the distribution substation). For simplicity, the photovoltaic systems were treated as if they were all identical and as if they were mounted on similar single-family homes.

The degree of photovoltaic penetration was not specifically defined but was assumed to be substantially less than 100% for the whole distribution system. Cost figures, however, were computed as if every house served by a given distribution transformer were equipped with a photovoltaic system, and the results were normalized with respect to the length of the associated distribution line (i.e. expressed on a per-mile basis) as though the photovoltaic penetration on that unit length were 100 percent. It was felt that expressing the results in these terms would facilitate their convenient extension to larger systems or to different degrees of penetration.

Although these restrictions on the scope of the inquiry limit the generality of the conclusions to some extent, it is believed that the results are broadly representative of conditions that would exist with other load categories, other utility system configurations, other photovoltaic designs, and other degrees of penetration.

2. Analysis Approach

The initial step in the approach used in this study was to select a particular baseline utility system configuration supplying the electrical demands of homes without photovoltaic generation systems, to define a conceptual design for the baseline distribution system, and to analyze the power handling capacity of the system. This baseline configuration was

defined to a level of detail that identified all major components and specified their ratings. The operation of the baseline design was then analyzed in the case where photovoltaic systems were present and feeding back excess power into the grid. The power levels through the various system components under these new conditions were determined and their effects analyzed in order to identify whether over-stress or unsafe operating conditions were introduced into the distribution system. The effects of fault conditions during steady state operation were investigated and evaluated in terms of the baseline protection and fault isolation design. All requirements for redesign or changes in configuration were then expressed in terms of the associated increases or decreases in capital cost relative to the baseline system cost.

3. Significant Findings

The analysis identified three changes in distribution system design that would be required before residential photovoltaic systems could be safely and reliably operated with power feedback to a utility line: a) an increase in distribution transformer capacity, b) improved secondary isolation capability (additional switches) on these transformers, and c) power factor correction. (The need for power factor correction is a consequence of the use of static inverters to convert the DC electric power from the photovoltaic array to the AC needed to serve the residential loads.) In addition, it was observed that, if any credit is to be assigned to the photovoltaic system owners for the feedback power delivered to the utility, a more sophisticated electrical energy metering system will be required.

It was estimated that the cost of increasing the ratings of the distribution transformers to accommodate the high peaks resulting from feedback photovoltaic power would amount to \$4200 per mile of distribution line. The cost of adding positive disconnect switches on the secondary sides of these transformers would be of roughly the same order, \$2300/mile, but the cost of power factor correction would be much larger, approximately \$30,000 per mile. Since the cost per mile of the distribution line in the baseline case is about \$27,000, these three extra items would add to the system costs an amount equal to 133% of the baseline figure. The total cost

of a utility distribution system, however, is heavily dominated by substation costs. Consequently, the cost of the above changes would amount to an increment of only about 15% of this total distribution cost. (Since the computation is carried out on a per-mile basis, these comparisons are based on the tacit assumption that there is 100% photovoltaic penetration of the small section of the grid that is being considered.)

The additional cost of providing metering capacity with the potential for separately measuring and recording the flow of electricity in both directions between the utility grid and the photovoltaic-equipped residence was estimated as between \$100 and \$400 per installation, depending on the degree of sophistication used in the measurements. This would correspond to incremental system costs, for the residential density of the baseline configuration, of between \$10,500 and \$42,000 per mile. The cost increase from recomplexing metering systems alone, therefore, could be in excess of 15% of the total distribution cost.

III. THE HYBRID PHOTOVOLTAIC/THERMAL-ELECTRIC POWER PLANT CONCEPT

1. Background

It is widely recognized that the principal obstacle to the wide-spread use of photovoltaic solar energy conversion as a general source of electricity is the high cost of the photovoltaic modules themselves. One promising approach to the overcoming of this obstacle is to employ optical concentration systems to collect large amounts of incident sunlight and direct it to relatively small photovoltaic cell assemblies. This procedure, in effect, replaces much of the expensive photovoltaic module area with an equivalent area of concentrating collector that is expected to be much less expensive (relative to current module prices, at least). A further potential advantage arises from the fact that, since the cost of the cell assembly in a high-concentration system becomes relatively insignificant in comparison to collector costs, one can afford to pay a significant premium for higher efficiency in the cell assembly. Higher efficiency, in turn, implies smaller collector area for a given output and therefore lower overall cost.

Analyses of high-concentration high-efficiency photovoltaic power plants (Refs. 5, 12) have tended to indicate, however, that such plants are unlikely to be competitive with conventional fossil-fuel generating plants until well after the year 2000 if the only salable product is the electricity from the photovoltaic cells. On the other hand, these studies have also shown that very large amounts of thermal energy must continually be removed from the photovoltaic cell assemblies in high-concentration plants in order to keep cell temperatures low enough for efficient conversion. If an economic use could be found for this surplus thermal energy, the competitive position of these plants might be substantially improved.

A preliminary investigation of possible power plant concepts in which this thermal energy is put to profitable use identified the hybrid photovoltaic/thermal-electric concept as potentially very attractive (Ref. 1). In this concept very high solar energy concentration ($X = 500 - 1000$)

is used in conjunction with high-efficiency ($\eta = 22\%$ at 20°C) AlGaAs/GaAs cell assemblies, and the thermal energy extracted from the cells is used in a low-pressure bottoming-cycle turbine-generator to produce additional electricity. This initial investigation, however, was only exploratory and was subject to some major limitations. While the effects of varying insolation and ambient temperature were considered in a qualitative manner, there were no simulation computations of plant operation. Instead the analyses were based very largely on hand calculations and, accordingly, system performance was evaluated only at selected insolation levels and for a very limited range of system parameters. Turbine off-design performance was not accounted for, nor was thermal storage included in the conceptual design. Because array cooling was assumed to be accomplished entirely by the sensible heating of liquid water, massive water flow rates were required and optimization studies were dominated by pump power requirements. Furthermore, only preliminary estimates were made of the cost and performance of such major thermal system components as the turbine and the heat rejection subsystem.

The objective of the study discussed in this section was to conduct a somewhat more thorough evaluation of the hybrid high-concentration photovoltaic/thermal-electric power plant concept with the aid of a more complete conceptual design (especially of the thermal-electric parts of the system), an appropriate computer simulation model, and more complete estimates of subsystem costs. The conceptual system design that was developed is presented in the next section of this report, Section III-2. This is followed by a description of the computer model that was developed to represent this system and a summary of the assumptions used in the economic analysis (Section III-3). The final subsection, Section III-4, contains a discussion of the results.

2. Conceptual Design

The specific system design that was evaluated in this study is illustrated in Fig. 1. The concentration system is in the central receiver configuration, in which a large field of steerable mirrors (heliostats) is

Figure 1
Photovoltaic/Thermal-Electric Plant Conceptual Design

used to reflect sunlight onto photovoltaic cells (AlGaAs/GaAs cells in this case) that are attached to the surface of a cylindrical receiver mounted on top of a tower. (The effective concentration ratio is assumed to be 1000.) The cells are cooled by water flowing in an annular passage just inside the surface of the cylinder. The annular passage also serves as a boiler in which the cooling water is heated and, at some point in the flow, brought to boiling temperature. The resulting mixture of pressurized hot water and steam is further heated and emerges from the upper end of the boiler as high quality, but not saturated, steam. This wet steam then flows to a steam drum or settling chamber where the water droplets settle out. The hot water from the steam drum is returned to the boiler at about the point where boiling begins (top of the "preheater"), while the now-saturated steam is either delivered directly to a low pressure turbine or is recondensed and stored as hot water in the storage tank. When thermal energy from the storage tank is needed, hot water from the top of the tank is flashed to steam and this steam is used to drive the turbine. After passing through the turbine, the steam is directed to the condenser/cooling tower (air cooling is used), condensed to hot water, and pumped back to the boiler. The D.C. electricity generated by the AlGaAs/GaAs cell assembly is converted to AC by power conditioning equipment, combined with AC power from the turbine-generator, and delivered to the load.

In the development of this conceptual design, a number of difficult choices had to be made on the basis of engineering judgement, supported by only very limited hard data. In more than a few of these cases, it is quite possible that another designer would have chosen differently. The complexity of the system and limitations on available resources, furthermore, made it impossible to carry out a complete optimization of even those design elements about which adequate data were available. For these reasons, although considerable care went into its definition, the conceptual design analyzed in this study may not represent the optimum configuration for a photovoltaic/thermal-electric power plant. It should be considered as representative rather than optimum, and any conclusions drawn from the operation of the computer model for this design should be treated as preliminary rather than definitive.

3. Simulation Model

The flow of the computations in the photovoltaic/thermal-electric plant model is illustrated schematically in Fig. 2. For each system simulation run, the input parameters listed in the upper left portion of the chart are specified. The computation begins with a "system sizing" run that determines the combination of turbine-generator rating and photovoltaic power conditioner rating which, after allowing for system losses (in pumping, power conditioning, conduction), yields the specified plant rating. With turbine-generator and power conditioner ratings specified, the simulation then computes a set of tables in which the AC output of the turbine-generator, the DC output of the photovoltaic array, and the system electrical losses are given as functions of the ambient temperature and of the amount of insolation incident on the photovoltaic cell assembly. Separate tables are computed for each mode of thermal-electric operation (solar energy to turbine, solar energy to storage, energy from storage to turbine, or appropriate combinations of these).

The program then proceeds to carry out an hour-by-hour computation of system performance on the basis of a magnetic tape record of hourly values for the insolation (both direct normal and total hemispheric) and for the ambient temperature at the site in question and over the period of interest. An algorithm that describes the performance of the system optics (the heliostat field and central receiver) computes the hourly amount of insolation that reaches the cell assembly. Hourly values for the turbine-generator output (AC) and array output (DC) are then obtained by interpolation in the tables discussed in the preceding paragraph (after identification of the mode of operation and therefore of the appropriate table to be used). The DC array output is then used as an input to the previously developed photovoltaic system simulation model that computes line losses, power conditioning losses, and losses in the electric storage subsystem (if any). The AC turbine output is similarly corrected for losses and added to the AC output of the power conditioner to yield the total plant output. These hourly results are then summed to provide data on the annual performance of the thermal-electric and photovoltaic portions of the system and of the system as a whole.

Figure 2
Photovoltaic/Thermal-Electric Plant Simulation Model

This plant performance information is then used as an input to the economic analysis. For the purposes of this study, the standard EPRI/ERDA levelized fixed charge approach (Ref. 13) was used and the levelized busbar energy cost was taken as the economic figure of merit. All inputs and results were expressed in terms of 1975 dollars. The fixed charge rate was set at 15%, a figure that is consistent with an after-tax discount rate of 8%, a general inflation rate of about 5%, and a plant service life of 30 years. It was assumed that the levelized operation and maintenance cost is a flat 3 mills/kWh. In these analyses no attempt was made to determine the effective capacity displacement that the introduction of the solar plant would accomplish, and no account was taken in the economic analysis of the cost of backup conventional capacity that might be required in order to preserve the reliability of the utility generation system if such a solar plant were substituted for a conventional one.

4. Results

The computer program described in the preceding section was first used in an initial series of runs to determine the effect of variations in some of the minor system parameters and thereby to develop information that would permit the confident assignment of appropriate fixed values for these parameters -- e.g. heat exchanger area, cooling tower mass flow rate, and the ambient temperature design point for the turbine. The program was then used in a matrix of runs in which the major system parameters -- collector area, electric storage capacity, thermal storage capacity -- were varied systematically from run to run in a search for an optimum design configuration. For these runs, it was assumed that the plant is located in Phoenix, AZ, and insolation data for that site in 1973 were used in the hour-by-hour simulation computations. The results are displayed in Figs. 3-5.

The computational results presented in Fig. 3 represent cases in which the thermal storage capacity is set equal to zero. The levelized busbar cost of electricity from the solar plant is plotted as a function of collector (heliostat) area. Each curve corresponds to a different value for the electric storage capacity, expressed in terms of the number of hours of operation, at the full rated capacity of the photovoltaic part of the

Figure 3
 Cost of Electric Energy as a Function of Collector Area for
 Various Electric Storage Capacities

Figure 4
 Cost of Electric Energy as Function of Collector Area
 for Various Thermal Storage Capacities

Figure 5

Cost of Electric Energy vs. Collector Area
 as Function of Combined Storage

system, that could be obtained from the storage when fully charged. The value of the overall plant capacity factor, PCF, is shown at each of the data points that was used in developing these curves. (The plant capacity factor is the ratio of the annual amount of electric energy produced by the plant to the amount that would have been produced if it operated at full rated capacity during all 8760 hours of the year.) The curves display a minimum because, for a given value of storage capacity, lower values of collector area fail to drive the electric power conditioner to rated output much (or any) of the time, thereby reducing the cost effectiveness of the power conditioner. High values of collector area, on the other hand, lead to the collection of more insolation than can be handled by the power conditioner; this excess energy is thus wasted.

The curves in Fig. 3 clearly indicate that in cases where there is no thermal storage capacity, minimum busbar energy cost is achieved when the electric storage capacity is also equal to zero. The plant capacity factors associated with the minima on all the curves are approximately 0.30. Since conventional plants serving the "intermediate" portion of the utility load have capacity factors in the 0.3 to 0.5 range, these solar plants could act as somewhat low-capacity intermediate-load plants. It is to be expected, of course, that in less favorable sites than Phoenix the plant capacity factors would be lower still.

The curves in Fig. 4 show the computational results obtained when the electric storage capacity is set equal to zero and thermal storage capacity is varied, while the curves in Fig. 5 correspond to cases where both types of storage are allowed to vary. As before, it is clear that minimum cost of electricity generation is achieved when both electric and thermal storage capacity is zero. (It should be noted, of course, that these results are somewhat sensitive to the assumed system and subsystem costs, especially the cost of the storage subsystems -- \$40/kWh for electric storage and \$56 per electric kWh for thermal storage. Although these values are based on what are believed to be reasonably optimistic projections of price reductions achievable by 1990, the realization of substantially lower storage prices could shift the economic balance toward favoring the use of storage.)

It is of interest to compare the minimum value of the busbar energy cost as shown in Figs. 3-5, just over 70 mills/kWh, with the cost of energy from a purely photovoltaic power plant using the same central receiver configuration. Since the performance of such a plant was evaluated in computer simulations carried out in earlier studies (Refs. 1, 5), it is only necessary to apply the same type of economic analysis (and the same cost figures for corresponding subsystems) in order to obtain a comparable figure. When this is done, the resulting value for the levelized busbar cost of energy from a purely photovoltaic central receiver plant at Phoenix is about 78 mills/kWh. It thus appears that the effect of adding the bottoming-cycle turbine to the system is to reduce the overall cost of electric energy generation by about 10%.

It must be noted that the above results are based on the initial set of runs with the new computer simulation program and therefore should be treated with appropriate caution. They are preliminary rather than definitive. As was pointed out in Section III.4, furthermore, the conceptual plant design reflected in the model has not been shown to be optimum. Care should therefore be exercised in drawing general conclusions from these results, even for Phoenix. Much more work remains to be done before final conclusions about the photovoltaic/thermal-electric plant concept are possible, but it is believed that the work reported here is a step in the appropriate direction.

IV. PROGRAM SUPPORT ACTIVITIES

The program support provided to the DOE managers of the National Photovoltaic Program has included participation in the many regularly scheduled meetings that have been used as vehicles for managing the program. These include, in particular, the monthly meetings of the ad hoc management committee consisting of DOE personnel and the project managers from the seven prime contractors involved in the program. Since the assumption by the Jet Propulsion Laboratory (JPL) of Lead Center responsibility for the Technology Development and Applications portion of the program this group has been formally designated as the Management Council. During the period covered by this report, four such meetings were held: on 7 September 1978 in Washington, DC; on 8 November 1978 in Crystal City, VA; and in Pasadena, CA, on 12 December 1978 and 30-31 January 1979.

The other regularly scheduled meetings have been the Semi-Annual Review Meetings of the Technology Development and Applications Program and the Project Integration Meetings (PIMs) of the JPL Low-Cost Solar Array (LSA) Project and of the Sandia Laboratories Concentration Technology Development Project. The only Semi-Annual Review Meeting during the report period was held on 7-9 November 1978 in Crystal City, VA, and the agenda included a presentation on recent results in this Aerospace Corporation Photovoltaic Mission Analysis Project. The LSA PIMs held during the report period took place on 16-17 August and 13-14 December 1978 in Pasadena, while the only Sandia PIM was held on 29-30 November in Albuquerque, NM.

In addition to these regularly scheduled meetings, Aerospace Corporation representatives have also participated in a number of other activities in support of the planning and management of the Photovoltaic Program. These have included contributions to the initial draft of the new Photovoltaic Multi-Year Program Plan (MYPP), reviews of successive drafts and assistance in preparing revisions of the MYPP, and participation in the deliberations of the ad hoc Goals Working Group whose task has been to provide an updated expression of program goals for incorporation into the MYPP. Program support activities have also included reviews of and suggestion of changes to other important program documents, most notably

a) the first draft of a Photovoltaic Commercialization Plan (prepared in the Office of the DOE Assistant Secretary for Conservation and Solar Applications) and b) the initial draft of the Photovoltaic Residential Applications Implementation Plan.

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