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PHOTOVOLTAIC MISSION ANALYSIS

PROGRESS REPORT
1 MARCH 1977 — 30 JUNE 1977

FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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PHOTOVOLTAIC MISSION ANALYSIS

Progress Report for the Period

1 March 1977 - 30 June 1977

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FOREWORD

This report presents an account of work accomplished during the period 1 March-30 June 1977 under Group F - Photovoltaic Mission Analysis (Tasks 8, 9, 10, and 12) of a project entitled "Solar Thermal Power Systems and Photovoltaic Solar Energy Systems Technical Support Services" and supported by the Division of Solar Energy, U.S. Energy Research and Development Administration (ERDA). Since the ERDA contract covering this work had not yet been finally negotiated at the close of the report period, no contract number has yet been assigned. Support for the work reported here was provided in the form of interim funding.

For the purposes of this report the tasks into which the effort is divided have been assigned different numbers from those listed in the Statement of Work (SOW) for the overall project: Task 1 (SOW Task 8), Photovoltaic Total Energy Missions; Task 2 (SOW Task 9), Intermediate-to-Large Load Center Applications for Photovoltaic Electricity; Task 3 (SOW Task 10), Incentive Strategies for the Photovoltaic Program; and Task 4 (SOW Task 12), Photovoltaic Solar Energy Program Technical and Management Support.

The work of the overall contract is being conducted by the Energy Systems Group of the Energy and Transportation Division of The Aerospace Corporation, under the overall management cognizance of Dr. A. B. Greenberg, General Manager of the Energy and Transportation Division. Dr. M. B. Watson, Director of the Energy Systems Group, is the Principal Investigator. Dr. H. L. Macomber is the ERDA Program Manager for the Group F tasks, and Dr. S. L. Leonard, Associate Director, Photovoltaics Projects, is the Aerospace Project Technical Manager for these tasks.

This report was prepared by Dr. S. L. Leonard, B. Siegel, and E. J. Rattin. The authors wish to express appreciation for the support of a number of other personnel of The Aerospace Corporation. Those include Dr. V. Chobotov, F. J. Collins, D. F. Gluck, D. J. Johnson, A. A. Mastor, P. L. Merryman, R. J. Swigart, and H. M. White. The help of R. G. Kramer and F. C. Eggers in overseeing the production of the report and of Ms. F. K. Morris in typing the text is also gratefully acknowledged.

ABSTRACT

This report covers the first four months of activity in a project whose overall objective is to support the planning, development, and guidance of the ERDA National Photovoltaic Program by a) identifying and evaluating those applications for terrestrial photovoltaic conversion of solar energy that are most likely to lead to significant contributions to the national energy supply, b) identifying and evaluating appropriate strategies for stimulating the growth of near-term (1977-1986) and mid-term (1986-2000) photovoltaic markets, and c) providing technical and documentation support to the ERDA Photovoltaic Program Office. In the current project, the effort to achieve these objectives has been divided among four tasks: Task 1, Photovoltaic Total Energy Missions; Task 2, Intermediate-to-Large Load Center Applications for Photovoltaic Electricity; Task 3, Incentive Strategies for the ERDA Photovoltaic Program; and Task 4, Photovoltaic Solar Energy Program Technical and Management Support.

A major initial thrust of the work under both Tasks 1 and 2 has been directed toward screening the large numbers of potential total energy system (PTES) and electric load center application in order to select the most promising candidates for detailed examination. Appreciable effort during the report period, accordingly, was devoted to the selection of an initial set of screening criteria and the accumulation of the data needed in order to apply the criteria. Of the nine criteria selected, all but two (ratio of thermal to electric demand, temperature requirement for thermal energy) are equally applicable in screening PTES and all-electric load center applications. An extensive data search was begun at the outset of the project and included interrogation of a number of different computerized information repositories and direct contact with a great many individual and group sources of information. At the close of the report period, the data search was still in full swing, but it was becoming apparent that there are some important limitations in the available data base. For example, there appears to be very little in the way of summary data on the numbers of floors in buildings of a given type or on the size of the exterior parking area or of the roof area for specified types of business enterprise. Information about regional variations in market growth projections, in structure size (for a given type of application), or in the size of the unit demand also appears to be lacking. As a result of the difficulty in locating some of these kinds of data and of delays that have been experienced in receiving needed documents, the data base at the end of the report period was still too limited to permit a formal screening to be carried out, either of PTES or electric load-point applications. On the basis of the data that were available, however, it was judged that a) among the applications considered, single-family residences and retail stores appear to offer the greatest

market potential, b) short-range farm motive power (i. e. electric tractors, farm machinery) and irrigation pumping may constitute an interesting combination PTES application because the energy demands tend to occur at different times of the year, and c) there appear to be a great many industrial process-heat applications for PTES.

The other main focus of activity during the report period was on some preliminary analyses of PTES applications and on the development of analytical tools for carrying out more detailed evaluations. A rough generalized study was made of the relative economic attractiveness of a) photovoltaic collector/array systems providing a combined thermal/electrical output and b) separate flat-plate solar thermal and electric (photovoltaic) panels. In the case when the combined collector was also a flat panel, the separate panels were found to be more desirable over most of the expected range of costs for photovoltaic arrays, solar thermal panels, and supporting structure. Under the same general conditions, however, a combined thermal/electric system using moderate concentration ($X \sim 50$) appears to be preferable to separate flat-plate thermal and electric panels over much of the United States. This reversal is largely a consequence of the fact that thermal losses from flat plate panels are much greater than those from concentrating systems unless expensive precautions (e. g. vacuum insulation) are taken with the design of the flat panels.

In addition, earlier evaluations (Ref. 2) of the use of a PTES in a single-family home in Phoenix, Arizona, were extended. An evaluation was made of the total annual cost of providing the required thermal and electrical energy to a homeowner whose electrically air-conditioned house is equipped with either a) a purely electric photovoltaic system that provides the needed thermal energy by resistive heating, b) a system incorporating separate flat solar thermal and photovoltaic panels, or c) a system using combined (flat) thermal/electric panels, supplemented by additional all-electric panels (air cooled photovoltaic arrays) to increase the electric energy fraction. In every case it was assumed that any required backup energy was obtained, in electric form, from the utility grid. For the Phoenix example studied, it was found that, if the photovoltaic array cost is less than $\sim \$300/\text{kW}_{\text{pk}}$, the lowest overall cost of service is that associated with option a), with option b) ranking second.

The work on the development of analytical tools for evaluating PTES applications took two forms. In the first, the simulation model used in the preliminary computations discussed above was examined to determine if it is fully adequate to identify the system configuration

that is optimum for providing both thermal and electric energy. At the end of the report period, the evaluation was still under way; if the procedure is found to need improvement, the necessary modifications will be made. The second tool-development effort has been directed toward construction of a computer model for simulating the hour-by-hour performance of a high-concentration photovoltaic/thermal-electric plant in which thermal energy removed from the (Al GaAs/GaAs) arrays is used to generate additional electricity in a bottoming-cycle turbine. At the end of the report period, algorithms to represent the boiler (array cooling system) and the heat-exchanger had been completed and work was proceeding on the turbine algorithm.

Work on Task 3 was started fairly late in the report period. The initial emphasis was on incentives for use in encouraging the deployment of user-owned photovoltaic systems for providing on-site electric power to large industrial or commercial consumers. The first step in the investigation has been the adaptation to these sorts of business enterprise of the existing Aerospace Corporation Utility Financial Planning Model. At the close of the quarter, the adaptation process was under way but had not progressed very far.

No effort was expended on the Task 4 activity during the reporting period. The Washington-based personnel required in order to carry out this task cannot be designated until after a final contract covering the effort has been negotiated and signed.

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I. INTRODUCTION

This section of the report contains a brief discussion of the objectives, background, and general organization of the study and a listing of the specific activities that were planned for the current reporting period, March 1 to June 30, 1977.

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Chart 1

OBJECTIVES AND STUDY ORGANIZATION

The study discussed in this report is designed to provide ongoing support to the U. S. Energy Research and Development Administration (ERDA) in its program to develop photovoltaic conversion of solar energy as an alternative method for meeting a significant portion of the national energy requirements. The overall objective of the study, along with the task breakdown and specific task objectives, is summarized in Chart 1.

The current investigation is a continuation of a study effort that began in 1974, under National Science Foundation (NSF) Grant No. GI-44099 (Ref. 1). The principal emphasis of the initial NSF-sponsored project was on the development of an appropriately detailed methodology for the technical and economic evaluation of candidate applications. The methodology was then exercised in the evaluation of some illustrative examples of applications in the southwestern United States in the 1980-2000 time period, most notably to a) the generation of on-site power for a single-family residence in Phoenix, AZ, and b) the generation of general utility power in central station photovoltaic plants in Phoenix and Inyokern, CA. The initial NSF study was followed by an ERDA-sponsored investigation (Ref. 2) under Project Agreement 8, Contract No. EY76-C-03-1101 (December 1975-February 1977), in which the primary emphasis was on an assessment of near-term (1976-1985) markets for photovoltaic arrays and on a continuing examination of such major mid-term (1986-2000) applications as central station power plants, with particular attention to the effects of geographic location and of the use of concentrating collectors. Lesser amounts of effort were devoted to three supplementary tasks: a) an investigation of the environmental and occupational hazards of photovoltaic array production, b) a preliminary evaluation of the effect of selected incentives on the economics of photovoltaic power plant operation, and c) an assessment of the total societal costs of coal-fired power generation.

As is indicated in Chart 1, the current program involves extensions of the earlier work in three main areas: photovoltaic total energy systems, intermediate-to-large load center applications, and incentive strategies. Photovoltaic total energy systems (PTES) are systems that provide both photovoltaic electricity and solar thermal energy to meet all or part of the energy demand at a single load point or a group of related load points. It is intended that the study consider the full range of PTES sizes, from systems on single family residences to those serving multi-megawatt industrial electrical and thermal loads. The study of intermediate-to-large load center applications for photovoltaic electricity is intended to fill in a

major gap in the coverage of the earlier studies, which did not identify or evaluate any potential on-site applications for systems larger than those required for single-family homes ($\sim 10 \text{ kW}_{\text{pk}}$) but smaller than central station power plants ($\sim 100 \text{ MW}_{\text{pk}}$). The incentives study will extend earlier work by evaluating some additional types of incentives for constructing photovoltaic central station plants and, more importantly, by evaluating incentives to encourage utilization of load center photovoltaic systems in each of the major sectors of the U. S. economy.

The fourth task listed in Chart 1 is substantially different from the other three. It entails the provision of direct support to the ERDA Program Office in the form of special analyses and studies and of assistance in the preparation of program documentation. Since these services will be provided on an as-required basis, they cannot, in general, be planned in advance and are therefore not included among the planned activities listed in the next chart, Chart 2.

Mission Analysis of Photovoltaic Solar Energy Systems

OBJECTIVES AND STUDY ORGANIZATION

OVERALL OBJECTIVE

TO SUPPORT THE PLANNING, DEVELOPMENT, AND GUIDANCE OF THE ERDA NATIONAL PHOTOVOLTAIC PROGRAM BY

- IDENTIFYING AND EVALUATING THOSE PHOTOVOLTAIC APPLICATIONS MOST LIKELY TO LEAD TO A SIGNIFICANT NATIONAL ENERGY CONTRIBUTION
- IDENTIFYING AND EVALUATING APPROPRIATE STRATEGIES FOR STIMULATING THE GROWTH OF NEAR-TERM (1977-1986) AND MID-TERM (1986-2000) PHOTOVOLTAIC MARKETS
- PROVIDING TECHNICAL AND DOCUMENTATION SUPPORT TO THE ERDA PHOTOVOLTAIC PROGRAM OFFICE

STUDY ORGANIZATION/TASK BREAKDOWN

TASK 1: PHOTOVOLTAIC TOTAL ENERGY MISSIONS

OBJECTIVE: TO IDENTIFY THE MOST PROMISING U. S. APPLICATIONS FOR PHOTOVOLTAIC TOTAL ENERGY SYSTEMS IN THE POST-1985 PERIOD

TASK 2: INTERMEDIATE-TO-LARGE LOAD CENTER APPLICATIONS FOR PHOTOVOLTAIC ELECTRICITY

OBJECTIVE: TO IDENTIFY THE MOST PROMISING APPLICATIONS FOR PHOTOVOLTAIC SYSTEMS PROVIDING ELECTRIC POWER TO INDIVIDUAL LOAD-POINTS OR TO GROUPS OF RELATED LOAD-POINTS

TASK 3: INCENTIVE STRATEGIES FOR THE PHOTOVOLTAIC PROGRAM

OBJECTIVE: TO EVALUATE ALTERNATIVE GOVERNMENTAL INCENTIVE STRATEGIES TO ENCOURAGE THE WIDESPREAD USE OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION

TASK 4: PHOTOVOLTAIC SOLAR ENERGY PROGRAM TECHNICAL AND MANAGEMENT SUPPORT

OBJECTIVE: TO PROVIDE ERDA PHOTOVOLTAIC PROGRAM MANAGERS WITH TECHNICAL AND DOCUMENTATION SUPPORT NEEDED FOR TIMELY AND EFFECTIVE PROGRAM DIRECTION

Chart 1

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Chart 2

PLANNED ACTIVITIES FOR THE PERIOD FROM MARCH 1 TO JUNE 30, 1977

The planned project activities for this reporting period are summarized in Chart 2. The principal initial task was to be the adoption of preliminary screening criteria and their application to the selection, for more detailed analysis, of promising candidate applications for photovoltaic total energy systems (PTES), under Task 1, and for purely electric on-site photovoltaic systems of intermediate-to-large size, under Task 2. A major part of this start-up effort is the collection of the information about potential applications that is needed in order to apply the screening criteria. Starts were then to be made on technical and economic analyses of the most promising mission of each type (photovoltaic total energy or intermediate-to-large purely electric) identified in the initial screening.

As Chart 2 suggests, it was planned that emphasis during this first quarter of activity be placed on Task 1. In addition to the data collection and initial screening activities, a critical examination of the existing PTES simulation procedures was scheduled, and a start was to be made on the implementation of any required improvements. The preliminary analysis of residential PTES applications, begun under the preceding ERDA contract (Ref. 2) and utilizing the existing simulation procedure, was also to be continued. Finally, it was planned that algorithms be developed for computing the energy transfers that occur when thermal energy collected in cooling the arrays in a high concentration photovoltaic power plant is used to generate additional electricity in a "bottoming cycle" turbine. These algorithms are then to be used in constructing computer simulation subroutines to be incorporated into the photovoltaic system model in order that a more detailed analysis can be made of the concept. (A preliminary analysis of this use of the thermal energy in a high-concentration plant, carried out under the preceding contract (Ref. 2) indicated that it may well be enough to make such plants economically competitive with conventional power sources.)

The planned effort on Task 2 was appreciably smaller than that on Task 1, being largely confined to the data collection and initial screening subtasks, although a start was also to be made on a more detailed analysis of the most promising one or two candidate applications.

It had originally been planned that work on Task 3 would begin at the start of the report period. Because of unavoidable delays in the assignment of appropriate personnel, however, a start was not made on this task until May 1; the corresponding entries in Chart 2 reflect this delayed schedule. The first planned activity is the adaption of the existing Aerospace

Corporation Utility Financial Planning Model to permit its use in studying the economics of user-owned photovoltaic systems in on-site commercial or industrial applications. A start was then to be made on the analysis of the effects of a selected group of incentive strategies on the economics of such systems.

Planned Activities for Period from March 1 to June 30, 1977

TASK 1: PHOTOVOLTAIC TOTAL ENERGY MISSIONS

- CONDUCT COMPREHENSIVE SEARCH FOR DATA ABOUT POTENTIAL APPLICATIONS FOR PHOTOVOLTAIC TOTAL ENERGY SYSTEMS (PTES)
- DEVELOP PRELIMINARY SCREENING CRITERIA
- SELECT ONE OR TWO PROMISING PTES APPLICATIONS FOR DETAILED ANALYSIS
- BEGIN ANALYSIS OF SELECTED APPLICATIONS
- BEGIN MODIFICATION OF COMPUTER MODEL FOR BETTER PTES SIMULATION
- CONTINUE PRELIMINARY ANALYSIS OF SINGLE FAMILY RESIDENTIAL PTES, USING EXISTING SIMULATION CAPABILITY
- DEVELOP ALGORITHMS FOR CONSTRUCTING COMPUTER MODEL FOR HIGH-CONCENTRATION CENTRAL STATION POWER PLANT WITH BOTTOMING-CYCLE TURBINE RUN BY THERMAL ENERGY

TASK 2: INTERMEDIATE-TO-LARGE LOAD CENTER APPLICATIONS FOR PHOTOVOLTAIC ELECTRICITY

- CONDUCT COMPREHENSIVE SEARCH FOR DATA ABOUT CANDIDATE LOAD CENTER APPLICATIONS
- DEVELOP PRELIMINARY SCREENING CRITERIA
- SELECT ONE OR TWO PROMISING APPLICATIONS FOR DETAILED ANALYSIS
- BEGIN ANALYSIS OF SELECTED APPLICATIONS

TASK 3: INCENTIVE STRATEGIES FOR THE PHOTOVOLTAIC PROGRAM

- ADAPT AEROSPACE UTILITY FINANCIAL PLANNING MODEL FOR APPLICATION TO EXAMINATION OF ECONOMICS OF USER-OWNED INDUSTRIAL OR COMMERCIAL PHOTOVOLTAIC SYSTEMS
- BEGIN EVALUATION OF EFFECTS OF SELECTED INCENTIVES

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II. PROGRESS

This section contains a discussion of the progress that has been made during the reporting period in the two general areas of activity that received most of the attention during the quarter: a) the data collection/application screening element of Tasks 1 and 2 and b) preliminary investigations of several different PTES topics. In addition to the work reported in this section, a start was also made on Task 3, Incentive Strategies for the Photovoltaic Program, with initial emphasis on incentives for the deployment of user-owned commercial and industrial on-site photovoltaic systems. As a tool in examining the effect of incentives in this sort of application, the Aerospace Utility Financial Planning Model is being adapted to reflect the economics of non-utility commercial enterprises. This adaptation process was still incomplete at the close of the report period and is therefore not further discussed in this report.

No effort was devoted during the reporting period to the direct program support activities of Task 4, largely because the appropriate personnel could not be assigned to the task in the absence of a signed contract covering this new type of activity.

A. Data Collection and Application Screening

A necessary first step in carrying out both Tasks 1 and 2 of this project has been the development of procedures for screening the very large numbers of possible photovoltaic applications in order to select, for more detailed examination, those with the greatest potential. The adoption of selection criteria and the collection of the data needed in order to apply the criteria are the two principal elements of this screening process and these two elements are strongly interactive. The type of information that is sought is determined by the nature of the selection criteria, but the choice of criteria, in turn, is influenced by the availability of the data needed in order to apply them. For example, since the generation of market statistics by primary research is very expensive and therefore outside the scope of this study, it is necessary to adopt selection criteria that can be applied on the basis of existing market information.

Since the variety of potential markets (both for PTES and for purely electric photovoltaic systems) is great, the task of collecting the necessary data for screening these many potential applications is a very substantial one. Much of the effort during the reporting period, accordingly, has been devoted to the data collection task, and this task is not yet complete. The markets that are being examined include those associated with residential buildings, both single-family homes and multi-family structures; with institutional buildings, such as

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schools, medical complexes, libraries, and museums; with commercial structures, such as retail stores, shopping centers, hotels, motels, and office buildings; and with industrial buildings, such as warehouses and factories of all kinds. The needs of such structures for electrical and thermal energy for lighting, appliances and machinery, space heating, and space cooling are being examined, initially, on a fairly general basis. More detailed evaluation will, of course, be required for those candidate applications that are chosen, via the screening process, for detailed study. In addition to these data on the energy requirements associated with structures, information is being assembled about possible uses of photovoltaic electricity and the associated solar thermal energy in industrial processes, especially those requiring low-temperature process heat, and in such agricultural operations as water pumping (for irrigation, livestock, or domestic use), light machinery, crop drying, etc.

The next several charts (Chart 3-19) summarize the progress that was made during this first reporting period in the data collection and application screening aspects of Tasks 1 and 2. The initial screening criteria are discussed in Charts 3-5, the data collection progress is illustrated in Charts 6-18, and the current status of the effort is summarized in Chart 19.

Chart 3

PHOTOVOLTAIC APPLICATIONS SCREENING

It is evident that there are a great many classes of current and potential photovoltaic applications, as well as subclasses thereof, corresponding to different sizes, configurations, locations, ages, and so forth. As was discussed earlier, this poses a requirement for means of selecting application classes for which photovoltaic power is technically feasible and economically reasonable, and of performing further screening to identify those applications with the highest potential. The large number of application classes and subclasses prevent use of quantitative selection criteria, since use of such criteria would require a certain amount of analysis for every case. It is, therefore, necessary to use qualitative criteria even though such criteria involve subjective judgment whose inherent risks are well understood. However, risks of mistaken judgment can be minimized by the design of a scoring method of evaluation involving collective judgment by a group of individuals knowledgeable in this field.

This approach, i. e., qualitative scoring using a weighted preferential matrix associated with group judgment, was selected for the screening of the applications being reviewed under this project, with weights adjustable for major classes of applications. The qualitative criteria cover both technical and market-related evaluation parameters, as indicated on Chart 3. Subsequent charts describe each of the 9 selection criteria identified for the screening activity and define the rating scale for each. Rating values are assigned on the basis of relative compatibility with photovoltaic power generation, as indicated below:

- 3 = High compatibility
- 2 = Average compatibility
- 1 = Poor compatibility
- 0 = Not compatible

Photovoltaic Applications Screening

- TO SELECT POTENTIALLY PROMISING APPLICATION CATEGORIES
- TO SELECT APPLICATIONS FOR DETAILED SIMULATION ANALYSIS

Chart 3

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CRITERIA RATINGS I

a. Thermal to Electric Ratio

Applications are clearly preferable whose thermal and electric energy demand match the ability of the photovoltaic total energy system (PTES) to produce these forms of energy, or which, at the least, are able to utilize all of the thermal energy produced. When flat plate, non-concentrating arrays can be used, such as for applications to heating and cooling of structures or for hot water process heat, PTES collectors using Si cells will operate at Th/E energy ratios between 3 and 6, depending on collector heat loss, time of day, and insolation conditions. Flat plate Si arrays can produce hot water at temperatures of up to 60°C (140°F) if thermal energy in this form is desirable. Low-concentration collectors, using Si cells for higher temperature applications up to about 90°C (200°F), will produce Th/E ratios as high as 8. High concentration GaAs arrays operating at temperatures up to 200°C (400°F) develop Th/E ratios of about 6.

When applications require more thermal energy than is available from the PTES collector, supplementary thermal panels or other heat sources are presumed available. When the temperature requirement of the application is compatible with the use of flat-plate collectors, a low Th/E ratio can readily be accommodated by supplementing the combined thermal/electric PTES collector with additional air-cooled electric-only panels. Such an application would also receive a high compatibility rating. It is recognized that a lower limit exists for thermal demand, below which it is uneconomic to use PTES panels, with the associated active heat transfer system. This minimum level has not been established and is consequently not considered during the screening process.

A low rating under this criterion implies only low compatibility for total energy system application but will not bias judgement on suitability for pure-electric system use.

Rating Basis

For a concentrating PTES, a Th/E ratio of less than 3 implies the possible dumping of thermal energy and the consequent loss of the economic value of this energy. Ratios between 3 and 8 imply a fairly good match between generation and demand, minimizing dumping or supplementary thermal energy generation. Ratios above 8 imply the need for supplemental

thermal collectors or for fossil energy sources for thermal energy, which may bring about higher life cycle costs for the installation. For the case of non-concentrating arrays, high Th/E ratios are not allowed to influence the rating to a major degree, although it is assumed that the requirement for addition of purely thermal absorber panels is a disadvantage in terms of cost and collector area requirements.

b. Temperature

Three temperature levels were considered important to the screening process. Residential and commercial applications require hot water or steam for space heating, domestic hot water, and for absorption air conditioning. The latter use requires thermal energy at temperatures from about 90°C (200°F) to 105°C (220°F), while about 60°C (140°F) is sufficient for space heating and domestic hot water supply. Industrial process heat applications have arbitrarily been limited to about 190°C (375°F) (to prevent average array temperatures exceeding ~200°C (390°F)). Temperatures up to 60°C (140°F) are readily available from non-concentrating flat plate water-cooled arrays using Si cells. It is not clear at what application temperature requirement the switch to concentrating systems should be made, and when GaAs arrays in a high concentration system would become preferable. It is assumed that 190°C process heat requirements will call for the use of relatively high concentration GaAs arrays.

Rating Basis

There are insufficient data at this time on which to base preference ratings for temperature requirements of potential applications, except for the knowledge that Si cell electric conversion efficiency decreases rapidly with increasing temperature, and that the step to higher-efficiency GaAs cells is costly. Ratings are therefore based on temperature steps largely determined by demand temperature levels up to the maximum of 190°C which is materials controlled.

c. Demand/Insolation Phase Relationship

The compatibility between a photovoltaic energy source and the requirements of a given application also depends strongly on the supply/demand phase relationships for both thermal and electrical energy. The ideal phase relation, of course, is that in which supply and demand

are roughly coincident in time, thereby minimizing the need for energy storage or for energy from backup sources. Phasing in which thermal demand lags supply is preferred to that in which demand leads because thermal storage losses would be greater in the latter case. (The stored energy would have been collected in the previous diurnal cycle.) In many cases, of course, the supply/demand phase relationship cannot be classified simply as lagging, leading, or coincident. For example, in the case of a three-shift industry, all three phase relationships are present. In such cases, the lower rating will be assigned.

Rating Basis

This criterion is unrelated to the quantitative relationships between insolation and demand but is based on implied storage and backup requirements resulting from leading, lagging, and coincident phasing.

d. Energy Density Match

This criterion is primarily of interest in relation to the evaluation of photovoltaic applications to structures. It attempts to provide a relative ranking of applications on the basis of required land area in excess of available roof area, in order to provide the energy needs of the structure from the solar source only. It measures the ratio of the energy received by the structure per unit roof area to the energy consumed by the structure, also per unit roof area. The computation of this ratio assumes inclined collectors mounted on a flat roof and so spaced as to avoid shadowing; thus only about 60% of the roof area is available for collection of solar energy. The energy density computation is based on an average daily demand in kWh/day during the highest demand season of the year. Energy demand exceeding that available from the insolation received by roof-mounted collectors could be satisfied by utility-supplied energy or other means such as use of additional land for collectors. The use of such other means of satisfying excess demand are assumed to offer cost disadvantages.

Rating Basis

If energy collectible on the roof is insufficient to meet the structure's energy demand during the maximum demand season, then either supplementary utility service or collector area excess to roof area is required. The former is considered undesirable because it reduces potential fossil fuel displacement; the latter involves added land and structural cost.

Ratios of energy available from insolation to energy demand in excess of 1 are desirable to permit some disparity in phasing and to allow accumulation of stored energy to compensate for periods of reduced insolation.

Criteria Ratings — I

• a. THERMAL TO ELECTRIC RATIO

• b. TEMPERATURE

• c. DEMAND/INSOLATION PHASE RELATIONSHIP

- 3 = COINCIDENT - IMPLIES MINIMUM STORAGE
- 2 = LAGGING - LOWER THERMAL STORAGE LOSSES SINCE STORAGE IS FILLED FROM INSOLATION ON SAME DAY
- 1 = LEADING - HIGHER THERMAL STORAGE LOSSES SINCE STORAGE IS FILLED FROM INSOLATION RECEIVED ON PREVIOUS DAY

• d. ENERGY DENSITY MATCH

Chart 4

CRITERIA RATINGS II

a. Market Growth Rate

Markets grow when removals from inventory as a result of wearing-out or obsolescence are exceeded by new additions. Significant photovoltaic penetration of markets with little or no growth would, in general, require retrofitting photovoltaic power into existing applications. Penetration of these markets may be more difficult because of institutional and financing factors. Photovoltaic applications in these areas will also probably be more expensive, as a result of the additional investment required to retrofit energy conservation measures in order to reduce energy consumption and make solar energy more cost-effective. New additions to the market imply energy conserving characteristics already integral to the design. In the field of structures, inventory growth has generally been between 1.5 and 2%, with specific types, such as shopping centers and malls, as well as fast-food franchises, growing much more rapidly.

Rating Basis.

Applications with higher growth rates are more desirable, with rates exceeding 2% per year between now and 1990 being preferred.

b. Market Size

Market size can be expressed by reference to a number of parameters. Considered most significant in view of national energy goals is that of fossil fuel displacement potential. It is to be noted that consumption of electric energy produced by steam plants translates to a fossil fuel consumption about three times as large when energy equivalents are compared. The losses in energy conversion are smaller for the conversion of natural gas, oil, diesel fuel and gasoline into usable thermal energy. This implies that this criterion should be concerned less with numbers of individual applications than with the total fossil fuel displacement that penetration of photovoltaics into a particular applications class could accomplish. Another major judgmental factor influencing the ratings awarded under this criterion will be the actual penetration, or percent of total available market, that solar energy might predictably attain.

Rating Basis

The total projected U.S. energy consumption in 1990 is 117 quads, of which 94.5 quads are from fossil sources. Applications classes which, upon maximum probable penetration, would produce fossil-fuel displacements exceeding 0.25 quads/year on a national basis are preferred.

c. Market Location

Specific residential, commercial, and industrial applications can exist predominantly in either rural, suburban, or urban environments or in combinations thereof. Agricultural applications are, of course, primarily rural, although some suburban areas still contain sizable agricultural components. Except for single family residences, urban area applications are collector-area constrained because of higher density of construction and greater use of multi-story construction. They may also have a greater collector shadowing problem because of height variations among neighboring structures. Smoke and smog will also contribute to reductions in insolation in urban areas. Locations can further be regionalized by relative insolation and by prevailing or anticipated pricing of competing energy sources. Electric energy costs vary by a factor of 7 over the nation, while natural gas costs can vary by as much as 6 and coal by 4. Land costs are also an important regional characteristic impacting solar energy cost-effectiveness.

Rating Basis

Photovoltaic power should be most competitive in regions of high insolation, high competitive energy cost, low structure density, and, for many application classes, in rural areas where land costs are lower. The rating for this criterion is therefore based on the relative strength of these four factors: insolation, fuel cost, structure density, and land costs.

d. Electric Power Demand Level

Level of demand of load points which are characteristic of an applications class is a useful criterion inasmuch as competing power sources appear to have more rapidly increasing unit cost of energy with decreasing load than do photovoltaic sources. Further, some of the competing sources have minimum sizes below which equipment limitations prevent effective power generation. There also exists the potential that a larger number of smaller load points will permit higher rates of production of photovoltaic units of similar design, thus allowing

learning curve effects to reduce unit cost. This factor also reduces development and engineering cost per unit. Further, lower unit investment cost should contribute to earlier adoption of the new technology. All of these factors point to increasing competitiveness of photovoltaic power in the instance of applications with smaller load demand.

Rating Basis

No information on optimum photovoltaic energy system size for the various potential applications is available at this time. Numerical ratings can therefore not be assigned. Application classes will be ranked by probable average unit electric demand, with preference afforded to the smaller demand levels.

e. Reliability Requirement

Photovoltaic solar energy conversion systems are subject to inherent limitations on service reliability because of the unavoidable diurnal, seasonal, and weather-related variations in insolation and because it is too expensive to provide sufficient energy storage (and the extra array area to fill the storage) to smooth out these variations. Applications requiring a very highly reliable energy source are therefore less compatible with photovoltaic systems than are applications in which an occasional outage can be tolerated.

Rating Basis

The numerical rating basis indicated in the chart is a somewhat arbitrary one, based on engineering judgment. It is possible that, as additional data become available, these rating assignments will be adjusted somewhat.

Criteria Ratings – II

a. MARKET GROWTH RATE

b. MARKET SIZE

c. MARKET LOCATION

ALL FOUR FACTORS ARE FAVORABLE	3
ONLY THREE FACTORS ARE FAVORABLE	2
ONLY TWO FACTORS ARE FAVORABLE	1
ONLY ONE OR NONE OF THE FACTORS ARE FAVORABLE	0

d. ELECTRIC POWER DEMAND LEVEL

NO RATINGS - TO BE RANKED BY AVERAGE UNIT ELECTRIC DEMAND

e. RELIABILITY REQUIREMENT

LOWER RELIABILITY REQUIREMENTS OF APPLICATION CLASSES REDUCE COST OF STORAGE AND OF STANDBY POWER

RELIABILITY REQUIREMENT	RATING
90% OR LESS	3
BETWEEN 90 AND 95%	2
BETWEEN 95 AND 99%	1
BETWEEN 99 AND 100%	0

Chart 5

Chart 6

DATA BASE

Progress in accumulating the data base required both for the initial screening activity and subsequent detailed analysis has been slow. Pertinent report bibliographies have been obtained from ERDA, Department of Defense (DoD), Department of Housing and Urban Development (HUD), the NTIS, The Smithsonian Scientific Information Exchange (SSIE), and from Aerospace Corporation resources. In addition, telephone contact with personnel in the Department of Agriculture, Bureau of the Census, Department of Commerce, and with a number of industry associations has produced some valuable data. However, delays in receipt of requested reports have prevented full utilization as yet of the data base which might be available from the published literature. The data received to date are voluminous and have only been partially analyzed. It does appear, however, that some data categories are especially sparse, e.g. information about the numbers of floors in multi-family dwellings as a function of region and size of housing project. It is particularly difficult to find all of the required data for applications evaluation from a single source so as to assure its internal consistency. For example, data on space heating requirements are often not associated with electrical demand for the same dwelling units, forcing the aggregation of the needed data base from sources which may differ in accuracy or which cover disparate regions, dwelling sizes, economic status of owners or renters, and so forth. Several of the data sources used heavily by other related studies have been found to contain contradictory data when compared among themselves and against Census data as a standard. This is true for housing data in References 3 and 4.

The primary data categories of interest relate to the selection criteria previously discussed. The data search is therefore oriented toward obtaining information necessary to the screening process, and its present status is discussed below in relation to each of the criteria.

Data Base

- BIBLIOGRAPHIES OBTAINED
 - ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
 - DEPARTMENT OF DEFENSE
 - DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT
 - NATIONAL TECHNICAL INFORMATION SERVICE
 - SMITHSONIAN SCIENTIFIC INFORMATION EXCHANGE
- DIRECT CONTACTS
 - DEPARTMENT OF AGRICULTURE
 - BUREAU OF THE CENSUS
 - DEPARTMENT OF COMMERCE
 - INDUSTRY ASSOCIATIONS
- STATUS
 - SLOW ACCRETION OF DOCUMENTS
 - ANALYSIS IS PROCEEDING
 - SOME DATA NOT AVAILABLE ON REGIONAL BASIS

Chart 7

DATA BASE: THERMAL/ELECTRIC DEMAND RATIO INDUSTRIAL EXAMPLES

Satisfying the data needs for application of the Th/E ratio criterion requires the correlation of information from often disparate sources. For example, Census data (Ref. 5) include information about total industrial fossil and electric energy consumption for each Standard Industrial Classification (SIC) code and thus allow the derivation of energy demand ratios on the basis of total industry demand. However, such gross energy ratio values are insufficient for application of the screening criterion. The evaluation of suitability for total energy application requires a segmentation of the fossil energy consumption of each industry into temperature regimes, because array temperature limits govern the fraction of the total thermal energy requirement of an individual industry which can be delivered by a photovoltaic total energy system. Refs. 6 and 7 provide some of the detailed information on industrial process heat requirements which allow this temperature-based segmentation, but do not provide much insight into the associated process electrical power needs. Other sources for detailed electrical demand data are still being sought. Examples of the industrial thermal-to-electric demand data available at this time are shown on Chart 7 for some industries for which at least some of the process heat requirements are at temperature levels suitable for photovoltaic total energy systems.

Data Base: Thermal/Electric Demand Ratio

INDUSTRIAL EXAMPLES

SIC	INDUSTRY	PROCESS TEMPERATURE °C	THERMAL ENERGY kWh x 10 ⁹	ELECTRIC ENERGY kWh x 10 ⁹	THERMAL TO ELECTRIC RATIO
2011	MEAT PACKING	30 - 95	18.5	4	4.6
2013	PREPARED MEATS	30 - 120	3.3	1.23	2.7
2016	POULTRY DRESSING	60 - 65	3.6	1.5	2.4
2026	FLUID MILK	75 - 95	9.5	3.2	3.0
2033	CANNED FRUIT & VEGETABLES	60 - 120	12.5	1.2	10.4
2046	WET CORN MILLING	45 - 50	19.5	1.9	10.3
2075	SOYBEAN OIL MILLING	70 - 175	11.3	1.4	8.1
2082	MALT BEVERAGES	60 - 175	12.0	2.0	6.0
2086	BOTTLED/CANNED SOFT DRINKS	25 - 75	4.8	1.1	4.4
2200	TEXTILE MILL PRODUCTS	30 - 230	66.5*	27.3	2.4
2400	LUMBER & WOOD PRODUCTS	95 - 150	63.2	15.3	4.1
2611	PULP MILLS	60 - 175	16.5	4.6	3.6

* Total Thermal Demand including those process segments exceeding PTES temperature limits.
 Note: Based on Ref. (6)

Chart 7

Chart 8

DATA BASE: THERMAL/ELECTRIC DEMAND RATIO RESIDENTIAL BUILDINGS

The usefulness of the Th/E ratio criterion in screening structural applications is questionable when only total annual electrical and thermal loads are used in determining the Th/E ratio. This is because wide swings in the thermal and electric load demand occur with changes in season in conventionally heated and cooled structures. This can change the value of the ratio from fractional minima to maxima exceeding 10. If absorption cooling is used instead of vapor compression-cycle cooling, the seasonal variations in the ratio are less pronounced and the ratio would in most cases remain above 1 in value. For this reason, it is desirable to determine this ratio separately for heating and cooling seasons.

Chart 8 illustrates the differences in residential Th/E ratios obtained for different demand periods and for different cooling methods. It is evident that PTES concepts appear feasible for single and multi-unit residences in most areas of the country when judged by this criterion, but primarily if absorption cooling is used. Vapor compression cooling reduces the effectiveness of PTES markedly during the cooling season.

Although a large amount of uncoordinated and sometimes contradictory information on residential and commercial structural energy demand is available, the computation of thermal-to-electric demand ratios has, to date, been feasible only in a gross sense. This is primarily a result of the necessity for correlating data from different sources, with different means of derivation, for housing units of different size, and for multi-family projects of different sizes. Considerable effort remains to be performed to derive data covering the breadth of combinations of application types, locations, and structural variants of interest to this program.

Data Base: Thermal/Electric Ratio

RESIDENTIAL BUILDINGS

DEMAND PERIOD	NORTHEAST	NORTH CENTRAL	SOUTH	WEST
a. <u>MULTIFAMILY TH/E RATIOS</u>				
<u>LOW RISE</u>				
ANNUAL BASIS	4.4	5.0	1.5	1.8
HEATING SEASON ONLY	8.9	10.6	4.6	4.2
COOLING SEASON ONLY:				
VAPOR COMPRESSION	0.69	0.63	0.54	0.49
ABSORPTION COOLING	1.2	1.6	2.4	3.2
<u>HIGH RISE</u>				
ANNUAL BASIS	3.8	4.3	1.5	1.7
HEATING SEASON ONLY	7.1	8.1	3.7	3.4
COOLING SEASON ONLY:				
VAPOR COMPRESSION	0.86	0.81	0.72	0.65
ABSORPTION COOLING	1.2	1.5	2.1	2.6
b. <u>SINGLE RESIDENCE TH/E RATIOS</u>				
ANNUAL BASIS	9.7	9.6	2.4	2.9
HEATING SEASON ONLY	14.4	16.6	8.5	7.2
COOLING SEASON ONLY:				
VAPOR COMPRESSION	0.93	0.84	0.64	0.54
ABSORPTION COOLING	1.9	2.6	4.4	5.7
NUMBER OF DAYS IN: HEATING SEASON	183	183	152	213
COOLING SEASON	91	91	183	122

Chart 8

Chart 9

DATA BASE: THERMAL/ELECTRIC DEMAND RATIO CORN DRYING

A considerable body of information on the energy requirements of farm operations, for various crops and types of livestock, has been assembled in Ref. 8 and in other documents published by a number of agricultural experiment stations in the country. In addition, the Agricultural Research Service of the Department of Agriculture, in collaboration with the NSF and with ERDA, is sponsoring research into the application of solar thermal energy conversion to farm needs. It is anticipated that much useful information will be available from such sources. Chart 9 exemplifies the type of information that appears to be available. The low values for the thermal/electric demand ratio that are presented in this table indicate that corn drying is not a very promising PTES application.

Data Base: Thermal/Electric Demand Ratio

CORN DRYING

	PRODUCTION 10 ⁶ BUSHELS	HEAT ENERGY IN DRYING (Btu x 10 ¹²)	FAN ENERGY IN DRYING (Btu x 10 ¹²)	THERMAL TO ELECTRIC DEMAND RATIO
IOWA	1,204	11.3	9.5	1.19
ILLINOIS	996	9.4	7.9	1.23
NEBRASKA	544	5.1	4.3	1.19
MINNESOTA	513	4.8	4.1	1.17
INDIANA	534	5.0	4.2	1.19
SO. DAKOTA	142	1.3	1.1	1.18
OHIO	240	2.3	1.9	1.21
WISCONSIN	173	1.6	1.4	1.14
MISSOURI	228	2.1	1.8	1.17
MICHIGAN	134	1.3	1.1	1.18
KANSAS	154	1.4	1.2	1.17
GEORGIA	80	0.8	0.6	1.33
NO. CAROLINA	114	1.1	0.9	1.22
PENNSYLVANIA	81	0.8	0.6	1.33
KENTUCKY	86	0.8	0.7	1.14
NEW YORK	5	0.05	0.04	1.25

Note: Data from Ref. 10

Chart 9

Chart 10

DATA BASE: TEMPERATURE: DEMAND/INSOLATION PHASE RELATIONSHIP

Temperature

As discussed earlier, surveys of industrial process temperature levels exist which permit derivation of the heat quantities demanded at various temperature levels for most industries. Structural space heating, water heating, and absorption cooling temperature requirements are relatively standard and thus a reasonable data base for the application of this criterion appears assured. For agricultural applications information about process temperature levels is also available from Ref. 10 and other sources.

Demand/Insolation Phase Relationship

Industrial load profiles on a hourly basis have not been reported in any of the data sources reviewed so far. Except for batch processes, such profiles tend to be relatively flat over each shift period. The total diurnal load profile would appear to be merely a function of the number of shifts worked. This will vary with industry, local institutional factors, and with product demand/supply relationships. For example, a continuous chemical process would generally operate in a three-shift mode, responding to demand changes by varying throughput rates, whereas batch processes could vary the number of shifts worked. The energy demand profile over a shift period would also be subject to considerable variation as a function of process variants within an industry. Considerable research into each application will therefore be required to complete the data base on industrial demand profiles.

Information on structural demand profiles is available from a limited number of sources where it is often synthesized rather than measured. Profile data are not available for many of the structure types and only spottily for the climatic regions of interest. This data category also will require considerable additional effort to complete. Very little published information has so far been found on the subject of load profiles for agricultural applications, although it may be possible to synthesize profiles from the descriptive data in the literature. Fortunately, however, the data requirements for the criterion, as used in the screening process, are essentially qualitative, as discussed earlier. For this reason it is not planned to acquire an extensive load profile data base on all of the applications to be subjected to the screening process, but to reserve that effort for the much smaller set of application classes selected for detailed analysis.

Insolation profiles are available at the Aerospace Corporation for about 33 locations in the U.S. As in the instance of the demand profiles, detailed insolation profiles will not be required for the screening process.

Data Base: Temperature, Demand/Insolation Phase Relationship

- TEMPERATURE
 - DATA ON INDUSTRIAL PROCESS TEMPERATURE LEVELS ARE AVAILABLE
 - INFORMATION ON THERMAL DEMAND TEMPERATURE LEVELS READILY AVAILABLE FOR:
 - STRUCTURES :
 - SPACE HEATING
 - WATER HEATING
 - ABSORPTION COOLING
 - AGRICULTURE
 - CROP DRYING
 - LIVESTOCK OPERATIONS, etc
- DEMAND-TO-INSOLATION PHASING
 - INDUSTRIAL LOAD PROFILES NOT YET OBTAINED - NOT READILY AVAILABLE
 - STRUCTURAL LOAD PROFILES LIMITED TO CERTAIN BUILDING TYPES AND LOCATIONS - MOSTLY SYNTHETIC RATHER THAN MEASURED
 - AGRICULTURAL PROFILES NOT YET OBTAINED
 - INSOLATION PROFILES AVAILABLE FOR 33 SITES IN U.S.

Chart 10

Chart 11

DATA BASE: ENERGY DENSITY MATCH RESIDENTIAL STRUCTURES INVENTORY

Insolation densities, i.e., energy received per unit area, are already defined for many points in the country. The data search for this criterion is therefore concentrating on defining energy demand and the available areas for collector installation that are associated with the various application groups. The energy demand data problem is similar to that already discussed in connection with the thermal-to electric ratio criterion. The requirement for data on available collector installation area is critical primarily for structures in urban areas, and is difficult to satisfy in these cases because sources of data on urban buildings usually do not include information about roof and parking lot areas. Some sources provide data on the total floor area of construction, others offer estimates of total numbers of units, still others provide information about the average floor area per housing unit. However, direct correlations between these quantities and the number of floors cannot be obtained from the literature, with only minor exceptions. These exceptions relate to residential data partitioned for buildings having 3 floors or less and 4 floors or more, without a distribution of the actual numbers of floors. Separate data on the average distribution of floors per structure are available from sources such as Ref. 11 which however, do not reveal the numbers of units, floor area per unit, or floor area per floor. Finally, data from different sources are often referenced to different years, ranging from 1964 to 1974. Chart 11 contains a summary of some of the residential inventory data that have been collected.

Chart 11 also shows the percentage of the residential inventory that is located in rural areas where the availability of land may make this criterion less important. For the same reason, this criterion would also be less important for agricultural applications, and for those industries generally located outside of urban areas.

Data Base: Energy Density Match

RESIDENTIAL STRUCTURES INVENTORY

TYPE OF STRUCTURE	NORTHEAST	NORTH CENTRAL	SOUTH	WEST	U. S. TOTALS	COMMENTS
<u>MULTI-FAMILY</u>						
<u>LOW RISE</u>						
AVERAGE AREA/UNIT, ft ²	880	860	900	910	884	} REF. 12, 13 REF. 3
AVERAGE No. OF FLOORS	2.2	2.4	2.3	2.2	TBD	
No. OF UNITS x 10 ³	5,944	4,459	3,991	3,136	17,530	
<u>HIGH RISE</u>						
AVERAGE AREA/UNIT, ft ²	TBD*	TBD	TBD	TBD	1,300	} REF. 12, 13 REF. 3
AVERAGE No. OF FLOORS	TBD*	TBD	TBD	TBD	4	
No. OF UNITS x 10 ³	2,235	456	341	263	3,295	
<u>SINGLE FAMILY, DETACHED</u>						
AVERAGE AREA, ft ²	1,353	1,308	1,247	1,372	1,300	} 1970 DATA (Ref. 14) NEW HOMES (Ref. 15) 1970 (Ref. 3)
1 STORY, %	45	62	85	78	73	
2 STORIES, %	38	20	11	14	17	
SPLIT LEVEL, %	17	18	4	8	10	
No. OF UNITS, THOUSANDS	7,778	13,261	15,683	8,079	44,035	
<u>URBAN AND RURAL</u>						
<u>MULTI-FAMILY</u>						
URBAN, %	93	89.8	82.6	91.1	89.6	} 1970 DATA (Ref. 17)
RURAL, %	7	10.2	17.4	8.9	10.4	
<u>SINGLE FAMILY</u>						
URBAN, %	TBD*	TBD	TBD	TBD	67	
RURAL, %	TBD*	TBD	TBD	TBD	33	

* TBD = Remains to be Determined

Chart 11

Chart 12

DATA BASE: ENERGY DENSITY MATCH NUMBERS OF STORIES IN MULTIFAMILY RESIDENTIAL BUILDINGS IN EAST SOUTH CENTRAL CENSUS REGION

Additional data will be required, as will considerable data manipulation, to derive sufficiently reliable estimates of the roof areas and, possibly, the parking lot areas that are associated with total floor areas for various residential and commercial building types on a national basis. The required data are available for several cities in the U. S. for which special surveys have been performed. In many of these cases, however, the survey sample was designed to determine typical building design rather than total inventory of various types of structures for the cities involved.

Chart 12 exemplifies some of the available data that may make it possible to derive approximate values for the roof areas associated with the total floor areas listed in the Census data. It indicates the proportion of apartment houses with 2 and 3 floors and allows an estimate of the error introduced by assuming that all multi-unit residential structures fall within these height categories.

Other commercial and industrial structures, such as retail stores, restaurants, warehouses, etc., being primarily single story (except in some highly urban areas), may pose less of a problem, but have not as yet been analyzed.

Chart 12

Chart 13

DATA BASE: MARKET GROWTH RATE
RESIDENTIAL STRUCTURES

Information about growth in the structures market is available from several forecasts in the literature, e. g. in the Phase O studies of solar heating and cooling that were carried out in 1973/74 under NSF sponsorship (Refs. 4, 13) and in the Project Independence report of the same vintage (Ref. 3). Conflict exists among these forecasts and insufficient independent data have been found to date to help resolve this conflict. The Census Bureau does not project future construction, and so its reports offer no standard of comparison. Projections in the literature appear to be based on utilization of population and economic growth predictions to modify trendline extensions of past construction growth. Chart 13 exemplifies the types of data that are available and some of the inconsistencies that are found. Of specific interest is the high growth rate shown by Ref. (3) for single family residences in the Northeast, when other data indicate that the South and the West should exceed the Northeast in growth.

Data Base: Market Growth Rate

RESIDENTIAL STRUCTURES

	NORTHEAST	NORTH CENTRAL	SOUTH	WEST	U. S. TOTALS	COMMENTS
<ul style="list-style-type: none"> • <u>DWELLING UNITS</u> <ul style="list-style-type: none"> • <u>MULTI-FAMILY</u> <p>FROM ANNUAL HOUSING SURVEY (Ref. 17)</p> <p>INVENTORY, UNITS $\times 10^6$</p> <p>AVERAGE GROWTH/YR, %</p> <p>FROM PROJECT INDEPENDENCE REPORT (Ref. 3)</p> <p>INVENTORY, UNITS $\times 10^6$</p> <p>AVERAGE GROWTH/YR, %</p> • <u>SINGLE FAMILY (Ref. 3)</u> <p>INVENTORY, UNITS $\times 10^6$</p> <p>AVERAGE GROWTH/YR, %</p> 						
	8.71	5.69	5.79	4.54	24.7	1975
	1.2	2.1	5.04	5.02	3.2	ACTUAL 1970-1975
	8.18	4.92	4.33	3.40	20.8	1970
	0.66	0.91	1.97	1.92	1.3	PROJECTION 1970-1990
	7.8	13.3	15.7	8.1	44.8	1970
	1.9	1.1	1.6	0.9	1.4	1970-1990
					(2.0)	(Actual 1970-75, from Ref. 17)
<ul style="list-style-type: none"> • <u>TOTAL ENERGY CONSUMPTION</u> <p>IN Btu $\times 10^{12}$</p> <ul style="list-style-type: none"> • <u>MULTI-FAMILY HOUSING</u> <p>CURRENT</p> <p>1990</p> • <u>SINGLE FAMILY HOUSING</u> <p>CURRENT</p> <p>1990</p> 						
	3,700	2,800	1,700	1,500	9,700	1975
	3,900	3,000	2,100	1,800	11,000	PROJECTION (Ref. 3)
	2,900	3,600	2,700	1,600	10,800	1970
	3,900	4,800	5,000	2,600	16,300	PROJECTION (Ref. 3)

Note: Total Energy Consumption is shown here as primary energy, i.e., all electrical point-of-use consumption has been converted to quantities of fossil energy required by the electric utility.

Chart 13

Chart 14

DATA BASE: MARKET GROWTH RATE COMMERCIAL STRUCTURES

Chart 14 shows projected growth for selected commercial structures, those with the highest floor space inventories. Retail stores appear to lead other structure types by a considerable margin.

As in the case of residential structures, conflict exists among various data sources, but independent growth projections are considered to be outside the scope of this study. The high growth rates shown on this chart for the Northeast based on data from Ref. (3) are believed indicative of incorrect removal rate assumptions.

Predictions of the growth of total industrial process heat requirements are to be found in the literature, e.g. in Refs. 6 and 7, but appear difficult to acquire for specific regions without extensive primary research at the state level as well as with a large number of specialist industry associations. These data also require reinterpretation for the temperature regimes specific to photovoltaic total energy applications.

Authoritative forecasts of agricultural energy consumption growth in sufficient detail for this program have not as yet been obtained. Such forecasts are, however, in preparation by the Department of Agriculture and may be available soon.

Data Base: Market Growth Rate

COMMERCIAL STRUCTURES

	NORTHEAST	NORTH CENTRAL	SOUTH	WEST	U. S. TOTALS
<u>OFFICE BUILDINGS</u>					
1970 FLOOR SPACE, (Note 1)	913	946	946	676	3380
1990 FLOOR SPACE	2570	2330	2610	1730	9240
GROWTH RATE, (Note 2)	5.3	5.2	5.2	4.8	5.2
<u>RETAIL STORES</u>					
1970 FLOOR SPACE	1094	1221	1137	758	4210
1990 FLOOR SPACE	3440	3720	3570	2300	13030
GROWTH RATE	5.9	5.7	5.9	5.7	5.8
<u>SCHOOLS</u>					
1970 FLOOR SPACE	1159	1411	1613	857	5040
1990 FLOOR SPACE	2110	2400	2680	1430	8620
GROWTH RATE	3.0	2.7	2.6	2.6	2.7
<u>HOSPITALS</u>					
1970 FLOOR SPACE	435	420	435	210	1500
1990 FLOOR SPACE	860	800	800	390	2850
GROWTH RATE	3.5	3.3	3.1	3.1	3.3

ALL DATA BASED ON REF. 3

Note 1: Floor space given in millions of square feet

Note 2: Growth rates are average annual rates predicted for the 1970-1990 period given in %

Chart 14

Chart 15

DATA BASE: POTENTIAL PHOTOVOLTAIC MARKET SIZE COMMERCIAL STRUCTURES

As was discussed earlier, the market-size screening criterion is concerned primarily with the potential magnitude of fossil energy displacement which could be accomplished by the application of photovoltaic power generation to a class of applications. Factors delineating candidate markets thus include the numbers of individual unit applications within a class, their unit energy consumption, and the national energy consumption for this class. Estimating the likely photovoltaic penetration of a large potential market is, of course, a considerably more complex process, since market penetration will depend on the special suitability of photovoltaic systems to the application in question (as measured, for example, by the scores received by the application in connection with the other screening parameters discussed in Charts 4 and 5). The initial screening criteria therefore do not include estimates of market penetration. It is expected, in fact, that quantitative estimates of market penetration will only be made for those applications classes which are judged, on the basis of the screening procedure, to be most promising.

Chart 15 provides market data on selected commercial building classes, those with highest energy consumption. On the basis of these preliminary data, retail stores appear to offer the largest potential market. No distinction is made on this chart between independent stores or those clustered into malls or shopping centers. Application of some of the other screening criteria will require such disaggregation.

Data Base: Potential Photovoltaic Market Size Commercial Structures

STRUCTURES	No. OF UNITS (Thousands)	TOTAL FLOOR SPACE 10^6 ft^2	TOTAL ENERGY CONSUMPTION 10^{12} Btu/Year
OFFICE BUILDINGS	523	3380	375
RETAIL STORES	1,980	4210	1790
SCHOOLS	159	5040	385
HOSPITALS	27	1500	108
HOTELS /MOTELS	49	1460 (Ref. 10)	188

Notes: Numbers of structures from Ref. 19
Floor area from Ref. 3, except as noted
Energy consumption computed from Ref. 19
Based on 1970 inventories

Chart 15

Chart 16

DATA BASE: POTENTIAL PHOTOVOLTAIC MARKET SIZE FARM OPERATIONS

Chart 16 shows a summary of those farm operations considered as candidates for photovoltaic energy application, including certain short range motive applications which might become technically and economically feasible if advanced battery development results in batteries of lower cost and higher energy density. Electric farm autos and trucks have not been included because of the longer travel distances which their use involves. On the other hand, tractors and self-propelled machinery (e.g. harvesters) appear to be earlier candidates for electric motive power because their radius of operation from a central recharge facility is no greater than several miles at most, and a highway recharge or battery exchange infrastructure would not need to be developed coincident with their introduction.

The data on this chart are extracted from Ref. 8 which shows the total energy consumption by U.S. Farm Operations (in 1974) to equal $1,298,000 \times 10^9$ Btu. On this basis, farm operations potentially suitable for photovoltaic or PTES application consume about 61% of all farm energy if short range motive power is included, and 33% if only stationary energy uses are considered.

Of the farm operations listed in the chart, irrigation is clearly the one representing the greatest consumption of energy. Irrigation consumes about 20% of the total on-farm energy consumption and about 60% of the energy consumed in stationary operations that were considered to be potential photovoltaic applications. Since this usage, of course, takes place mainly during the growing season, from April through September, a photovoltaic system for providing electricity only for irrigation pumping would necessarily waste a substantial amount of energy collected during the fall and winter seasons. Considerable economic advantage could probably be derived if the array output can be put to alternative uses in the off-season (e.g. for charging batteries for electric tractors or for crop drying).

Data Base: Potential Photovoltaic Market Size

FARM OPERATIONS

	CURRENT ENERGY USAGE (1974)		TOTAL Btu x 10 ⁹	POTENTIAL PHOTOVOLTAIC USE
	ELECTRICAL Btu x 10 ⁹	FOSSIL FUELS Btu x 10 ⁹		
<u>CROP OPERATIONS</u>				
PREPLANTING	-	139,103	139,103	ELECTRIC TRACTOR POWER
PLANTING	-	38,044	38,044	ELECTRIC TRACTOR POWER
CULTIVATING	-	43,174	43,174	ELECTRIC TRACTOR POWER
IRRIGATION	65,748	195,004	260,752	PUMP POWER
HARVESTING	-	141,398	141,398	ELECTRIC TRACTOR & MACHINERY POWER
CROP DRYING	2,928	102,383	105,311	RESISTANCE HEATING OR PTES
<u>LIVESTOCK OPERATIONS</u>				
LIGHTING	5,641	-	5,641	
WATER SUPPLY	5,478	3,301	9,049	PUMP POWER
SPACE HEATING	594	5,326	5,920	RESISTANCE HEATING OR PTES
VENTILATION	6,874	-	6,874	FAN POWER
WATER HEATING	3,328	6,719	10,047	RESISTANCE HEATING OR PTES
MILKING	2,800	-	2,800	MACHINERY OPERATION
MILK COOLING	4,587	-	4,587	VAPOR COMPRESSION OR PTES
BROODING	-	24,250	24,250	RESISTANCE HEATING OR PTES
<u>TOTALS</u>	97,978	698,702	796,950	
WITHOUT MOTIVE POWER APPLICATIONS			435,231	

Note: Based on Ref. (8). All farm operations consume 1,298,000 Btu x 10⁹ in U.S.

Chart 16

Chart 17

DATA BASE: MARKET LOCATION COST OF ELECTRICITY TO INDUSTRIAL CONSUMER, BY STATE

In order to determine the geographic distributions of the various candidate markets being screened, it is necessary to have available a great deal of statistical information that is segregated on a geographic basis. Although many types of data are, indeed, recorded separately by state, by SMSA (Standard Metropolitan Statistical Area), or even, in some cases, by county, city, or census tract, many of the categories of data that are of interest in this study are readily available only in the form of national totals. Among these latter, for example, are reports and predictions of growth rates in total floor area of various types of buildings or in requirements for low-temperature process heat. At the close of this report period, the search for regionally segregated data of these types was still in progress.

For application of the market-location criterion, information is also needed about regional variations in such factors as the price of energy from competing sources, the amount of available insolation, and the average local structure density. Fortunately, data on energy costs are available on a regional basis, although they are not always sufficiently current. One example of this type of information is displayed in Chart 17, which shows the cost of electricity to industrial customers, by state. For the purposes of this study it will be necessary to compile similar data for residential, commercial, and agricultural customers and to include the costs of energy in the form of coal, oil, and natural gas.

Insolation data are also readily available. In the course of earlier mission analysis work at The Aerospace Corporation, an extensive insolation data base has been accumulated. It now contains at least two years of hourly insolation data (both normal-incidence insolation and total hemispheric insolation) for 33 different sites in the United States. In addition, data on daily total insolation are available for a number of additional sites and for many more years of record.

Information about structure density, i.e., the number of buildings of a certain type per unit land area, as a function of location, appears more difficult to obtain from the published literature and may have to be dealt with qualitatively in the application of this screening criterion.

Data Base: Market Location **Cost of Electric Energy to Industrial Consumers by State** **in \$/1000 kWh, 1974**

Chart 17

Chart 18

DATA BASE: DEMAND LEVEL, RELIABILITY REQUIREMENTS

Demand Level

Data on unit demand are relatively easy to obtain for residential and commercial structures. If necessary, such data can be synthesized, sufficiently accurately for screening purposes, from standard values of various types of demand per unit floor area. Industrial unit demand information is more difficult to obtain since the Census data do not include statistics on individual plants. However, data on the numbers of employers within two-digit SIC codes for specific areas, and distributions of these employers as functions of the number of employees, are available. Correlation between per capita energy demand in a specific industry and numbers of employees for a specific employer may therefore provide a value for the demand level that is quantitative enough for screening purposes. Data on farm size distribution will be used in a similar manner.

Reliability Requirements

Data on quantitative reliability requirements, or permissible numbers of hours of power outage per year, are not easily found in the literature for most application classes of interest. Such requirements can be inferred, however, from the nature of the application and from the presence or absence of standby power generation equipment in common usage for specific applications. A qualitative ranking of applications should thus be feasible. The data search will consequently include a quest for information on current means of providing standby or back-up power for each application under consideration.

Data Base: Demand Level and Reliability Requirements

- DEMAND LEVEL

- UNIT ENERGY DEMAND FOR STRUCTURES AVAILABLE FROM LITERATURE OR FROM COMPUTER SYNTHESIS FOR TYPICAL STRUCTURES
- UNIT DEMAND FOR INDUSTRIAL PLANTS CAN BE APPROXIMATED FROM PER-CAPITA (employees) DEMAND
- FARM UNIT DEMAND CAN BE SYNTHESIZED FROM ACREAGE AND LIVE-STOCK STATISTICS

- RELIABILITY REQUIREMENTS

- EXPLICIT RELIABILITY LEVELS USUALLY NOT QUOTED IN LITERATURE FOR MOST APPLICATION CATEGORIES
- QUALITATIVE RANKING MAY BE REQUIRED

Chart 18

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SUMMARY: DATA COLLECTION AND APPLICATIONS SCREENING

The extent of the data base available for the applications screening process cannot as yet be judged because of delays in receiving requested reports and other data. It is clear, however, that some difficulty will be faced in applying the Energy Density Match criterion to the residential and commercial structures market. The statistics required to determine roof-area-to-contained-floor-area ratios do not appear to be available for multi-story buildings. Data on available parking lot area associated with such buildings also appear not to be available, except for isolated cases. Similarly, it may prove to be impossible to obtain information about regional variations in such important screening parameters as projections of the growth of energy consumption in various classes of potential applications. The Census does not provide projections, and data from other sources are insufficiently partitioned by region. Application of the Thermal/Electric Demand Ratio criterion may also be restricted, in the case of agricultural applications and applications involving energy supply for structures, by the scarcity of data on seasonal variations in this ratio. In the case of industrial process heat applications, however, seasonal influences should be small and the use of annual figures in computing the ratio should be adequate.

As a result of these limitations in the data base that has been assembled so far, the planned formal screening procedure has not yet been initiated. The currently available data have permitted some preliminary identifications of promising applications. For example, on the basis of potential market size, market growth potential, and general structural configuration, single family housing appears to offer greater fuel displacement potential (16 quads versus 11 quads) than multifamily housing. Long range market growth predictions (1970 to 1990) show almost equal rates of growth for single and multi-family housing, i.e. 1.4% to 1.3%. Even though recent experience (1970 to 1975) indicates a considerably higher growth rate for multifamily housing, i.e., 3.2% to 2%, this may be related to short-term economic factors induced by the recession of 1974-1975. Data on available collector area associated with multifamily projects, which are important in evaluating the energy density match criterion, have not yet been assembled and analyzed. It is probable, however, that much of this market will rank low when judged by this criterion because its predominantly urban location and its multifloor construction practices are expected to constrain available collector area. In the instance of single family residences, urban location does not significantly impact available collector area since roof areas appear sufficient in most insolation regions to meet electrical and thermal energy demand.

Among commercial building applications, it is noted that retail stores offer the greatest fossil fuel displacement potential, i.e. 1.8 quads versus 0.39 quads for schools, the next highest energy consuming commercial or institutional building class. Retail stores also have the highest projected growth rate (5.8% for the 1970 to 1990 period) in terms of floor space and, thus, presumably, in energy consumption, although future energy conservation measures may slow the growth of energy consumption per unit area. Next in growth rate magnitude is the office building category with an average annual rate of 5.2%. This category offers a fossil energy displacement potential slightly smaller than that for schools (0.38 quads versus 0.39 quads in 1970) but its predominantly urban location may reduce its attractiveness for PTES application.

The agricultural market segment is the smallest of the market segments reviewed, consuming about 1.3 quads (in 1974) in all direct farm operations. Energy consumption in irrigation operations amounts to about 20% of this total and is exceeded in magnitude by short range mobile operations such as planting, cultivating and harvesting. These operations, performed by machines which could be battery powered, have an interesting time-phased relationship with irrigation operations in that they are mostly performed prior to and after the growing season. Irrigation is the dominant energy consuming operation during the growing season. A photovoltaic energy generating facility, scaled to meet irrigation power needs, could therefore experience an increased annual utilization period by recharging electrically powered mobile equipment. It is believed likely that battery powered mobile farm machinery could be introduced earlier than highway vehicles because the short radius of operation of the farm equipment avoids the need for an extensive battery recharge or replacement infrastructure on the nation's highways, a need which handicaps introduction of electric powered vehicles in general.

The extensive list of industries utilizing low temperature process heat, and exhibiting thermal/electric ratios within the range of interest for PTES, offers considerable promise for photovoltaic application. Industrial applications will be investigated more intensely during the next reporting period.

Summary: Data Collection and Application Screening

- DATA BASE FOR SCREENING
 - DELAYS EXPERIENCED IN DATA INFLOW
 - POOR DATA BASE IN NUMBERS OF FLOORS, PARKING AREA, OTHER AREAS AVAILABLE FOR COLLECTORS
 - POOR DATA BASE FOR REGIONALIZATION IN DATA CATEGORIES SUCH AS GROWTH PROJECTIONS, SIZE OF STRUCTURES, AND SIZE OF UNIT DEMAND
- SCREENING
 - FORMAL SCREENING NOT YET INITIATED
DATA BASE CURRENTLY INSUFFICIENT
 - PRELIMINARY SCREENING INDICATES
 - SINGLE RESIDENCES AND RETAIL STORES OFFER GREATEST MARKET POTENTIAL
 - SHORT-RANGE FARM MOTIVE POWER AND IRRIGATION ARE COMPLEMENTARY IN DEMAND PHASING
 - MAY CONTRIBUTE TO PTES FEASIBILITY ON FARMS
 - MANY POTENTIAL INDUSTRIAL PTES APPLICATIONS EXIST

Chart 19

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B. Photovoltaic Total Energy Systems (PTES)

In parallel with the data collection and application screening activity discussed in the preceding charts, work has also been going forward on several analytical studies relative to PTES applications. In the first of these, illustrated in Charts 20 and 21, comparisons have been made of the total cost of providing the same amounts of electrical and thermal energy either by means of separate flat-plate electric-only and thermal-only collector panels or by a) a flat combined thermal/electric collector panel or b) a concentrating ($X=50$) combined thermal/electric panel. The second study, discussed in Charts 22-26, represents a continuation and extension of the examination of PTES applications in single-family homes that was begun in the previous study (Ref. 2). The third analytic activity (Chart 27) has been the development (not yet complete) of algorithms for computing the magnitudes of the energy transfers that occur when a bottoming-cycle turbine is incorporated into a high-concentration photovoltaic power plant. These algorithms will be used in the construction of a computer model for a photovoltaic plant in which thermal energy removed from the arrays by an active cooling system is used to generate additional electricity in such a turbine.

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Chart 20

COMBINED THERMAL/ELECTRIC PANELS VS. SEPARATE PANELS: FLAT-PLATE PHOTOVOLTAIC TOTAL ENERGY SYSTEMS

In Chart 23 are presented the results of a generalized comparison of the total cost of providing identical amounts of electric and thermal energy either by means of flat combined thermal/electric panels or by separate flat electric-only (photovoltaic) and solar thermal panels. The variables represented by the horizontal and vertical axes of the graph are the cost of the support structure for the electric panel in the separate-panel alternative and the total installed cost (including support structure) of the thermal panel. (It was assumed that the total installed cost of the combined thermal/electric panel is equal to the sum of the installed cost of a separate thermal panel plus the cost of a photovoltaic array of the same area).

The straight lines in the graph represent combinations of these variables that, for a given photovoltaic array price, lead to equal collector-system costs for the two alternative methods of providing electric and thermal energy. Points lying above and to the left of each line represent cases for which the separate-panel alternative is preferred (i.e. cheaper), while points on the other side of the line correspond to cases for which the combined panel is the preferred alternative. The point indicated by the black dot (electric panel support structure cost = \$10/m², thermal panel cost = \$50/m²) corresponds to the parameter values that were used in the preliminary analysis of residential PTES applications in the preceding study (Ref. 2).

The basic message that can be derived from this chart is that, when only flat panels are considered, separate electric and thermal panels are to be preferred over combined thermal/electric panels for most likely combinations of the variables that were considered. The preference for separate panels is only reinforced if a) less favorable solar energy sites than Inyokern are considered, b) a larger radiation absorption coefficient (than 0.77) is assumed, c) sites having colder winters are considered, or d) a larger heat-loss coefficient is assumed.

(Actually the results shown in this chart were obtained in a generalized computation of energy inputs and energy losses, on an annual-average basis. The figure used for the annual average of the convective and radiative thermal losses from a thermal panel was obtained by the equation

$$\mu_L^* \Delta T = (\mu_L/3) \Delta T = .0015 (50) = .075 \text{ kW/m}^2$$

where

$$\mu_L = 4.5 \text{ W/}^\circ\text{C} - \text{cm}^2 = .0045 \text{ kW/}^\circ\text{C} - \text{m}^2$$

is the value for the heat loss coefficient suggested in Ref. 12, for a single-glazed flat-panel of more-or-less conventional design. This value is divided by 3 in the above relation in order to correct for the fact that thermal losses only occur when the water in the panel has been heated by solar energy to a temperature significantly above the ambient, or only for about 8 hours out of every 24.)

Combined Thermal/Electric Panel vs Separate Panels

FLAT-PLATE PHOTOVOLTAIC TOTAL ENERGY SYSTEMS

LOCATION: INYOKERN, CALIF
 AVERAGE AMBIENT TEMPERATURE: 18°C
 AVERAGE OPERATING TEMPERATURE,
 THERMAL ARRAY: 68°C
 HEAT LOSS COEFFICIENT: $4.5 \text{ W/}^{\circ}\text{C} - \text{cm}^2$
 PHOTOVOLTAIC ARRAY EFFICIENCY (28°C): 0.15
 THERMAL/ELECTRIC ENERGY RATIO: ~ 3.7

DOMAIN WHERE COMBINED PANEL IS PREFERRED
SHRINKS WHEN:

- AVERAGE COLLECTED INSOLATION DECREASES
- RADIATION ABSORPTION COEFFICIENT IS INCREASED
- AVERAGE AMBIENT TEMPERATURE IS REDUCED
- HEAT LOSS COEFFICIENT IS INCREASED

BASIS FOR COMPARISON:
 COMBINED THERMAL/ELECTRIC PANEL AND
 SEPARATE PANELS HAVE IDENTICAL ANNUAL
 ELECTRICAL AND THERMAL ENERGY PRODUCTION

Chart 20

Chart 21

PHOTOVOLTAIC TOTAL ENERGY SYSTEMS: COMBINED THERMAL/ ELECTRIC CONCENTRATING COLLECTORS VS. SEPARATE FLAT PANELS

A rough generalized computation similar to that shown in the preceding chart was also carried out in order to compare the economic attractiveness of a concentrating ($X \sim 50$) combined thermal/electric solar collector with that of separate flat-plate thermal and electric (photovoltaic) panels. In this case, it was assumed that the concentrator had an annual average optical collection efficiency of 0.65, about what can be achieved with a north-south oriented parabolic trough. The photovoltaic cells used with the concentrator were assumed to be special concentrator-type cells, with AM1 efficiencies of 20% at 28°C , costing $\$100/\text{m}^2$. These figures are consistent with projections offered at the recent ERDA Photovoltaic Concentrator Workshop held in Phoenix, AZ, on May 24-26, 1977. The installed cost of the concentrator, itself, was left as a variable parameter. Thermal losses in the concentrating collector were neglected in the computation. (In effect, it was assumed that the collector embodied good thermal design, with vacuum-jacket insulation.) In the case of the separate flat panels it was assumed that a) the installed cost of the thermal panel (including any support structure) is $\$50/\text{m}^2$ and b) the cost of the support structure for the purely electric panel is $\$10/\text{m}^2$. The photovoltaic array efficiency (at 28°C) was assumed to be 15% (AM1), but the cost of the array modules was left as a variable parameter. Thermal losses from the flat thermal panel were treated in the manner described in connection with the preceding chart.

A comparison was then made between the costs of collector systems of these two types under the constraint that exactly the same amount of thermal and electrical energy is delivered to the load. The results are shown in Chart 24. The variables represented by the horizontal and vertical axes in the graph are the photovoltaic array price (in the flat-plate panels) and the installed cost of the concentrator assembly. The straight lines represent those combinations of the variables, for a given system location, that lead to equal collector-system costs for the two alternative methods of providing the thermal and electric energy. Points above and to the left of the lines represent cases when it is less expensive to use separate flat panels than to use a concentrating combined collector. Points on the other side of the lines represent cases when the concentrating combined collector is preferred. The chart indicates that in the colder regions of the United States the concentrating combined panel will be preferred when its cost (exclusive of photovoltaic cells) is less than $\$120\text{-}150/\text{m}^2$. In the warmer regions, the concentrating collector will be preferred when its cost is less than $\sim \$70/\text{m}^2$, if flat-plate photovoltaic arrays cost $\$100/\text{kW}_{\text{pk}}$, or less than $\sim \$120/\text{m}^2$, if flat-plate photovoltaic arrays cost $\$500/\text{kW}_{\text{pk}}$.

Photovoltaic Total Energy Systems

COMBINED THERMAL/ELECTRIC CONCENTRATING COLLECTOR vs SEPARATE FLAT PANELS

COMBINED PANEL:
 CONCENTRATION RATIO: 50
 ARRAY EFFICIENCY: $\eta(28^\circ\text{C}) = 0.20$
 $\eta(68^\circ\text{C}) = 0.176$
 PHOTOVOLTAIC ARRAY COST: $\$1000/\text{m}^2$
 CONCENTRATOR OPTICAL EFFICIENCY: 0.65
 THERMAL/ELECTRIC ENERGY RATIO: ~ 3.5

SEPARATE PANELS:
 ARRAY EFFICIENCY: $\eta(28^\circ\text{C}) = 0.15$
 COST OF SUPPORT STRUCTURE FOR
 ELECTRIC PANEL: $\$10/\text{m}^2$
 COST OF THERMAL PANEL (installed): $\$50/\text{m}^2$

BASIS FOR COMPARISON:
 COMBINED THERMAL/ELECTRIC COLLECTOR
 AND SEPARATE THERMAL AND ELECTRICAL
 PANELS HAVE IDENTICAL ELECTRICAL AND
 THERMAL ENERGY PRODUCTION

Chart 21

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Chart 22

RESIDENTIAL PTES STUDY

The preliminary study of residential PTES application that was begun under the previous contract (Ref. 2) has been continued and extended during the current reporting period. In particular, a comparison has been made of the total annual (levelized) costs of meeting, by each of three different photovoltaic system options, the thermal and electrical energy demands of a single-family residence in Phoenix, Arizona. The three system options, all employing flat-plate collectors, are:

- 1) All-electric photovoltaic. Passively air-cooled photovoltaic panels provide electricity to meet both electrical and thermal demand.
- 2) Separate systems. Solar thermal panels provide thermal energy, while passively air-cooled photovoltaic panels serve the purely electric demand.
- 3) Combined thermal/electric panels. Water-cooled photovoltaic panels provide both thermal energy (transported by the cooling water) and electrical energy to meet the separate thermal and electrical demands. Additional passively air-cooled photovoltaic panels are added, as required, to meet the electrical demand.

In every case, it is assumed that the required backup energy is provided (in the form of electricity) by the local utility system. It is further assumed that the homeowner is the owner of the solar system, that the system is mounted on the roof of the residence, and that the homeowner has the choice of installing a solar system or of purchasing all of the required energy from the local utility.

The study is oriented toward answering two questions,

- 1) For a given system option, what combination of panel area, storage, and utility backup provides minimum annual cost to the homeowner for various assumptions with respect to costs and system operation?
- 2) What is the effect of photovoltaic array cost on the relative attractiveness of each solar system option?

A general discussion of the approach used is presented in the following charts and the results of a few interesting cases are shown for a single family home in Phoenix. It should be noted that the approach developed appears capable of rapidly evaluating the impact on annual cost of many of the factors affecting the performance of solar systems in residential applications, including thermal and photovoltaic panel efficiencies, subsystem costs, utility power cost, homeowner vs. utility ownership, charges in demand due to location or alternative subsystem concepts (heat pumps, absorption air conditioning, etc), and feedback of excess power to the utility.

Residential Photovoltaic Total Energy Systems Study

- COMPARISON OF THREE FLAT PLATE SYSTEM OPTIONS, SINGLE-FAMILY PHOENIX RESIDENCE
 - ALL-ELECTRIC PHOTOVOLTAIC PANELS
 - SEPARATE SOLAR THERMAL AND ELECTRIC (photovoltaic) PANELS
 - COMBINED THERMAL/ELECTRIC PANELS
- ANALYSIS DEFINES FOR GIVEN SET OF ASSUMPTIONS
 - MINIMUM ANNUAL COST SYSTEM FOR EACH OPTION
 - LOWEST COST OPTION AS FUNCTION OF PHOTOVOLTAIC ARRAY COST
($\$/kW_{pk}$)

Chart 22

Chart 23

SYSTEM PERFORMANCE SIMULATION

In general the levelized annual cost of any of the solar system options can be considered as the sum of the levelized annual costs of capital, operation, and maintenance, plus that of the backup energy purchased from the utility. Simulation computations of system operation are required in order to determine the amount of energy provided by a solar option as a function of the principal parameters that affect system cost, such as panel area and storage level.

Typical results from such a computer simulation are shown in Chart 23, for the special case of a Phoenix, Arizona residence served by a photovoltaic system incorporating combined thermal-electric panels. The graphs represent the fraction of the annual demand for thermal energy that is provided by the solar panel, as a function of panel area and thermal storage capacity. Curves of similar shape and trend are obtained when other locations are considered or when it is the delivery of electrical, rather than thermal, energy that is being computed. In general, as the panel area is increased with storage capacity held constant, a larger fraction of the energy generated is simply wasted (as a result of mismatches between available energy and the demand) and the amount of energy actually delivered to the load approaches a limit. Similarly, as the storage capacity is increased for fixed panel area, energy that would otherwise be wasted is instead stored for use at a later time; as a result a larger fraction of the demand is met by solar energy and the amount of required backup energy is reduced.

System Performance Simulation

LOCATION: PHOENIX

ANNUAL THERMAL DEMAND: 10,370 kWh

Chart 23

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Chart 24

LEVELIZED ANNUAL COST OF ENERGY

When the amount of solar energy delivered to the load has been determined as a function of panel area and storage capacity (through simulation computations like those illustrated in the preceding chart), the next step is to calculate the total annual cost of meeting the energy demand. This is accomplished by adding the cost of the required backup energy (obtained from the utility grid) to the levelized cost of the solar energy. This latter amount depends, of course, on the assumed costs of the various elements of the solar energy system and on the effective levelized fixed charge rate that is adopted. Chart 24 illustrates the type of results that are obtained in such a computation. The upper curve in the chart shows the levelized annual cost of the thermal energy required by a typical single-family home in Phoenix, as a function of panel area. In this particular case, the solar panel was taken to be a combined thermal-electric one, the thermal elements (i.e. everything but the photovoltaic modules) of which were assumed to cost \$50/m², installed. The system was assumed to incorporate 50 kWh of thermal storage (at \$10.66/kWh). The chart shows that at a panel area of about 30 m² the levelized annual cost to the user is a minimum and equal to about \$400 per year (including the cost of backup energy from the utility grid). At panel areas smaller than the optimum, the incremental cost of the additional thermal energy resulting from incremental increases in panel area is less than the cost of backup utility power, while at larger panel areas the converse is true.

The horizontal line labeled "Annual Cost of Utility Power" is the levelized annual cost to the user if all the thermal energy required were purchased from the utility. (In this analysis it has been assumed that the cost of utility energy is constant regardless of the amount of energy purchased. In general, the cost of utility energy varies with the amount of energy purchased and the fraction of utility generating capacity provided by solar power). For the case shown, the levelized annual cost of thermal energy from the solar panel is less than the cost of utility energy if the panel area is larger than about 5 m² and smaller than about 75 m². By also displaying on Chart 24 the amount of thermal energy delivered to the load, as a function of panel area (right hand vertical scale), the relationship between thermal energy delivered by the panel and the total levelized annual cost can be presented. Note that in general, the amount of solar thermal energy delivered at minimum levelized annual cost is significantly less than the total demand (in this case about 75% of the total), and that large increases in levelized annual cost are required to significantly increase the amount of solar energy delivered to the load.

Results with the same general characteristics as those shown in Chart 24 are obtained, regardless of whether thermal or electrical energy is being provided by solar panels or whether separate or combined panels are considered. In general, at a given storage level, (1) there is a panel area that will minimize the total annual cost of energy; (2) the amount of solar energy delivered at the minimum annual-cost point is generally less than the annual demand; and (3) annual costs rise rapidly as the energy delivered by a solar panel approaches the total annual demand.

Levelized Annual Cost of Energy

THERMAL ENERGY,
RESIDENTIAL PTES, PHOENIX

Chart 24

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Chart 25

EFFECTS OF CHANGES IN SYSTEM AND COST ASSUMPTIONS

The results of calculations of the levelized annual cost of service (e.g. those illustrated in the preceding chart) obviously depend strongly on the system parameters and on the assumed costs of the major subsystems. The sensitivity of the results to changes in some of these assumptions is illustrated in Chart 25. The example shown to illustrate these effects is a calculation of the levelized annual cost of electric service to a single-family Phoenix residence that is equipped with passively air-cooled photovoltaic arrays.

The left-hand figure shows that as the cost of the photovoltaic array increases at a given electrical storage level, the levelized annual cost increases and the optimum panel area decreases. In other words, as the cost of photovoltaic power increases, it becomes desirable to purchase more of the energy required from the utility (it is again assumed that utility power costs 5¢/kWh). Conversely, if the cost of utility power increases relative to the cost of photovoltaic power, the minimum levelized annual cost will occur at larger panel areas. This suggests an approach where, initially, small photovoltaic panels are installed and then, as the cost of panels is reduced, more panel area is added. This procedure would minimize homeowner annual costs if the cost of utility backup power either remains constant or does not decrease more rapidly than the cost of photovoltaic panels.

The effect of electrical storage on levelized annual cost is shown in the right hand figure of Chart 25, where the array cost is fixed at \$100/kW_{pk}, but electrical storage capacities of 0, 25, and 50 kWh are considered. In general, increases in storage level increase the panel area at which minimum levelized annual cost occurs, with the optimum storage level determined primarily by assumed storage costs. An interesting modification in residential system operations which is related to the storage issue has been suggested by General Electric Co. investigators (Ref. 21). This modification would allow excess electrical energy generated by a photovoltaic panel, energy that would otherwise have been wasted, to be instead sold back to the utility at a given price. The utility becomes, in effect, an infinite storage "sink" for excess residential electrical energy, and the user receives revenue for energy that would otherwise have been wasted. Such revenue would, of course, reduce the effective levelized annual cost. The dashed line in Chart 28 shows, for the zero electrical storage case, the effect of selling this energy to the utility at 1¢/kWh. (This is 20% of the assumed cost to the user of buying utility power, 5¢/kWh in this example.) Note that if the price the utility is willing to

pay for this energy is zero, the solid curve labeled zero storage results. (This is equivalent, as far as the user is concerned, to wasting the energy). It can be seen that as the price the utility is willing to pay increases from zero, larger panel areas become more desirable and the levelized annual cost decreases.

Effects of Changes in System and Cost Assumptions

• PHOENIX • ANNUAL ELECTRICAL DEMAND: 17,440 kWh

Chart 25

Chart 26

COMPARISON OF ALTERNATIVE RESIDENTIAL PTES OPTIONS

The approach illustrated by the preceding three charts has been used to determine the minimum levelized cost of thermal and electrical energy for the same single-family Phoenix residence that has been used as an example in the earlier charts. The total annual energy demand is taken to be 27,810 kWh, of which 10,370 kWh is in the form of thermal energy for space heating and domestic hot water. The annual electrical demand is 17,440 kWh for baseload power (lights, appliances) and for air conditioning. It is assumed that no feedback of excess photovoltaic power to the grid is permitted (or, at least, that the homeowner receives no recompense for such power). Chart 26 summarizes the results of this analysis, for three different home-owner options:

(a) Buy air cooled photovoltaic panels that provide only electrical energy and use this energy, in combination with utility backup, to meet both the thermal and electrical demand. (The cost of utility power is assumed to be 5¢/kWh). The solid and dashed curves labeled (1) show the minimum levelized annual cost and the fraction of demand that is met by solar energy (right side vertical axis) for this option. Each point along these curves represents a minimum levelized annual cost system, with a specific array area and electrical storage. As the photovoltaic array cost increases, the minimum levelized annual cost increases, and the fraction of demand provided by solar energy decreases. Eventually, at an array cost slightly in excess of \$500/kW_{pk} (point A) it becomes less expensive to purchase all the required energy from the utility, at 5¢/kWh.

(b) Buy separate flat plate solar thermal and air cooled photovoltaic panels to provide thermal and electrical energy, respectively, and use utility power at 5¢/kWh for backup energy (curves labeled (2)). The thermal panel area and thermal storage are optimized for the thermal load, for an assumed panel cost of \$50/m². (In this case, the installed cost of the solar thermal system would be about \$100/m², which is understood to be a 1990 cost objective for the ERDA solar heating/cooling program). The minimum levelized annual cost of thermal energy in this case is about \$400 and the amount of solar thermal energy delivered is about 7400 kWh (about 71% of the thermal demand and 25% of the total demand). To this is added the cost of the electrical energy delivered to the load by the air-cooled photovoltaic panel and that obtained, as backup, from the utility grid. As the photovoltaic array cost increases, the cost of the thermal energy and the amount of solar thermal energy delivered remains constant, but

the amount of electrical energy delivered by the photovoltaic array at minimum levelized annual cost decreases and the cost of this energy increases. At about $\$390/\text{kW}_{\text{pk}}$ (point B), it becomes less costly to purchase all of the required electrical energy from the utility at $5\text{¢}/\text{kWh}$.

(c) Buy combined photovoltaic thermal panels that provide both thermal and electrical energy plus air cooled photovoltaic panels for additional electrical energy and purchase backup utility power at $5\text{¢}/\text{kWh}$ (curves labeled (3)). The area of the combined photovoltaic/thermal panels and the thermal storage capacity are optimized for the thermal demand on the basis of this assumption that the cost of the thermal portion of the combined panel is $\$50/\text{m}^2$. The minimum levelized annual cost of thermal energy in this case is calculated to be $\$430$ and the amount of solar thermal energy delivered is about 7400 kWh , which is identical to the amount of solar thermal energy delivered by the purely solar thermal panel discussed above. As the photovoltaic array cost increases, (1) the thermal energy cost, amount of solar thermal energy delivered, and photovoltaic/thermal panel area remain constant, (2) the amount of photovoltaic electrical energy delivered at minimum levelized annual cost decreases, and (3) the minimum levelized annual cost of electrical energy delivered increases. At a photovoltaic array cost of $\$320/\text{kW}_{\text{pk}}$ (point C) it becomes less costly to purchase all the electrical energy required from the utility at $5\text{¢}/\text{kWh}$.

Although the curves presented in Chart 25 represent a restricted range of cases, incorporating some specific cost and performance assumptions, it is still possible to draw some tentative conclusions from them:

1) The minimum levelized cost of energy under option (b) (separate solar thermal and air-cooled photovoltaic panels) is always smaller and the fraction of demand met by solar energy is always larger than under option (c) (combined photovoltaic/thermal panels) if the photovoltaic array price is in excess of $\$100/\text{kW}_{\text{pk}}$ and the solar-thermal panel cost is $\$50/\text{m}^2$ (installed). (Compare curves (2) and (3).) This result is due primarily to the higher thermal and electrical efficiencies of separate flat plate thermal and photovoltaic panels relative to those of a combined panel.

2) A system using an air cooled photovoltaic panel to generate electricity to satisfy both thermal and electrical loads (option a) leads to a lower value for the minimum levelized

annual energy cost than does a system using separate thermal and photovoltaic panels (option b) if photovoltaic array costs are less than about \$320/kW_{pk} (Point D). Similarly, option (a) leads to lower energy cost than does a system using combined photovoltaic/thermal panels (option c) if photovoltaic array costs are less than about \$400/kW_{pk} (Point E).

It is emphasized that the results presented are for a home in the Phoenix area with specific thermal and electrical loads and with utility power costing 5¢/kWh. Changes in insolation, total demand, or load profile as a result of changes in geographic location or the use of heat pumps or absorptive cooling could significantly alter these results. In addition, changes in the assumed future costs and efficiency of thermal panels or the sale of excess electrical energy to the utility grid could also greatly modify the results presented. Future analyses will attempt to evaluate the effects of each of the factors noted and develop more generalized conclusions on the relative desirability of the different flat plate photovoltaic total energy options.

Residential System Comparisons

- SINGLE FAMILY HOME IN PHOENIX (total demand = 27,810 kWh;
10,370 kWh thermal, 17,440 kWh electrical)

Chart 26

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Chart 27

PHOTOVOLTAIC/THERMAL-ELECTRIC POWER PLANT

Previous studies (Ref. 2) have indicated that the economic attractiveness of a high-concentration photovoltaic power plant might be considerably enhanced if the thermal energy extracted in cooling the photovoltaic arrays could be used to generate additional electricity in a bottoming cycle turbine. The specific configuration that has been suggested for such a photovoltaic/thermal-electric plant is illustrated schematically in Chart 27. The concentration system is in the central receiver configuration, in which a large field of steerable mirrors is 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 cells are cooled by a fluid flowing in an annular passage just inside the surface of the cylinder. The heated coolant fluid is then used to drive a low-pressure turbine or, alternatively, its thermal energy is transferred (in a heat exchanger) to a secondary fluid that drives the turbine.

Because past analyses have been based on hand calculations, it has only been possible to evaluate system performance at selected insolation levels and for a very limited range of system parameters. In these earlier analyses, furthermore, only preliminary estimates were made of the cost and performance of such thermal system components as the turbine and the thermal storage subsystem. In order to develop a better understanding of the operation of such a system and of the effects of variations in critical system parameters, detailed simulation computations are required. For this reason one of the early task elements of the current project is the development of a suitable mathematical model for making such simulation computations. To this end, algorithms for simulating the operation of the "boiler" (array-cooling system), the turbine, the thermal storage subsystem, and the cooling tower are being developed. These algorithms will then be integrated into the existing computer program for simulating photovoltaic power plant operation, and the resulting simulation model will be used in computations leading to:

- 1) Definition of thermal component size and cost and selection of working fluids.
- 2) Evaluation of alternative thermal electric system concepts such as using a secondary fluid to drive the turbine rather than the boiler coolant, wet and dry cooling towers, and boiling fluid cooling of the photovoltaic array.
- 3) Determination of appropriate levels of thermal and electric storage.

4) Overall system performance, including the effects of daily and seasonal variations in insolation.

At present, algorithms for the boiler (array) and cooling tower have been completed and programming of these algorithms will begin in July. In addition, an investigation into the availability of large, low temperature turbines is being conducted as part of the development of the turbine algorithm. There do not appear to be commercial turbines available for the operating temperature expected, (turbine inlet temperature is limited to about 350°F by the maximum allowable temperature of the gallium arsenide cells that are mounted on the boiler) and turbine size required. Estimates of turbine R&D and production costs will be developed on the basis of study results and of information obtained from manufacturers.

Photovoltaic/Thermal-Electric Power Plant

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III. PROJECT STATUS AND PLANS

In this section, the current status of the project and plans for the succeeding quarter are summarized.

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Chart 28

PROJECT STATUS - 30 JUNE 1977

The current status of the project effort is presented in summary form in Chart 28. Most of the entries in the chart are self-explanatory and refer to activities that are discussed in detail in connection with the preceding charts of the report. One exception is the last entry under Task 1, which refers to an effort, currently underway, to upgrade the PTES simulation procedure that was available at the start of the report period. This procedure, which was used in preliminary analyses of residential PTES in the predecessor study (Ref. 2), involves separate simulation and optimization of the thermal and electrical elements of the system. The current investigation is aimed at establishing if such separate simulation computations are adequate, i. e. if the parameters that separately optimize electrical and thermal energy production lead to an overall energy production optimum, or if it will be necessary to develop methods for simulating the simultaneous operation of the electrical and thermal systems.

Additional exceptions are the entries for Task 3, since the work on this task is not discussed elsewhere in the report. In this case, the principal activity has been the modification of the existing Aerospace Corporation Utility Financial Planning Model for application to evaluating the economics of user-owned commercial and industrial photovoltaic systems (either electric-only or PTES). This Financial Planning Model, which is described in detail in Vol. IV of Reference 2, was used in the earlier study to evaluate the impact of a selected group of incentives on the economics of the operation of a photovoltaic power plant in an electric utility system. Work on modifying the model to fit on-site user-owned photovoltaic systems was begun late in the reporting period and was still in progress at the close of the period.

One major activity of the project that is not represented in Chart 28 (or otherwise discussed in this report) has been direct support to the activities of the ERDA Photovoltaic Program Planning Group (PPG). This support has taken the form of participation in a number of working meetings, the preparation of portions of the planning documents that have been generated by the group, and analyses and calculations in support of the planning activity. The results of this work are reported separately by the Program Planning Group itself and are therefore not further discussed here. Also not shown in Chart 28 are a number of other project efforts in support of the ERDA Photovoltaic Program during the quarter. These have included, in particular, participation in such diverse activities as a) the monthly Project Managers'

Interface Meeting, b) the Photovoltaic Concentration Systems Workshop, c) the Semi-Annual Review Meeting of the Advanced Materials Research and Development Branch, d) the Quarterly Project Integration Meeting of the Low Cost Silicon Solar Array Project, and e) a meeting to evaluate proposals received in response to a Sandia RFP for Regional Conceptual Design and Analysis Studies for Residential Photovoltaic Systems.

Project Status – June 30, 1977

- TASK 1: PHOTOVOLTAIC TOTAL ENERGY SYSTEMS
 - INITIAL SCREENING CRITERIA SELECTED
 - DATA COLLECTION STILL UNDER WAY
 - SEVERAL PROMISING CANDIDATES IDENTIFIED IN PRELIMINARY SCREENING
 - SINGLE-FAMILY RESIDENCES
 - RETAIL STORES
 - PRELIMINARY COMPARATIVE ANALYSIS MADE OF THREE RESIDENTIAL PTES OPTIONS
 - DEVELOPMENT OF ALGORITHMS FOR PHOTOVOLTAIC/THERMAL-ELECTRIC PLANT SIMULATION IN PROGRESS
 - ALGORITHMS FOR BOILER (ARRAY), COOLING TOWER COMPLETED
 - ASSESSMENT OF PTES SIMULATION CAPABILITY IN PROGRESS
- TASK 2: INTERMEDIATE-TO-LARGE LOAD CENTER APPLICATIONS FOR PHOTOVOLTAIC ELECTRICITY
 - INITIAL SCREENING CRITERIA SELECTED
 - DATA COLLECTION STILL UNDER WAY
 - RETAIL-STORE APPLICATION IDENTIFIED AS PROMISING CANDIDATE IN PRELIMINARY SCREENING
- TASK 3: INCENTIVE STRATEGIES FOR THE PHOTOVOLTAIC PROGRAM
 - UTILITY FINANCIAL PLANNING MODEL BEING MODIFIED FOR ECONOMIC ANALYSIS OF USER-OWNED COMMERCIAL/INDUSTRIAL PHOTOVOLTAIC SYSTEMS

Chart 28

Chart 29

PLANNED ACTIVITIES - 1 JULY - 30 SEPTEMBER 1977

Project plans for the next quarter are summarized in Chart 29. As is indicated there, the main thrust under both Task 1 and Task 2 is to complete the data collection and application screening efforts and then to get on with the analysis of the most promising candidates. In the case of the PTES analyses, it is also expected that the question of the adequacy of the currently-available simulation procedure (involving separate optimization of the thermal system and the air-cooled electric system) will be resolved and, if the verdict is negative, that an improved procedure will be developed. Under Task 1, it is also planned to complete the development of the algorithms needed for constructing a simulation model for a high-concentration photovoltaic/thermal-electric power plant. By the end of the quarter, construction of the model should also be well under way.

In the Task 3 incentives analysis effort, it is planned to complete the task of adapting the existing Utility Financial Planning Model to deal with general commercial and industrial enterprises. A start will then be made, using the revised model, on the evaluation of alternative incentive strategies to encourage the deployment of user-owned photovoltaic systems in businesses of these types.

Planned Activities: 1 July to 30 September 1977

- TASK 1: PHOTOVOLTAIC TOTAL ENERGY SYSTEMS
 - COMPLETE DATA COLLECTION
 - CONDUCT FORMAL SCREENING OF POTENTIAL APPLICATIONS, IDENTIFY PREFERRED CANDIDATES
 - COMPLETE DEVELOPMENT OF IMPROVED PTES SIMULATION MODEL
 - BEGIN ANALYSIS OF PREFERRED CANDIDATE APPLICATIONS; EXTEND ANALYSIS OF PTES FOR SINGLE-FAMILY RESIDENCE
 - COMPLETE DEVELOPMENT OF ALGORITHMS FOR PHOTOVOLTAIC/THERMAL-ELECTRIC PLANT MODEL, PROCEED WITH CONSTRUCTION OF MODEL
- TASK 2: INTERMEDIATE-TO-LARGE LOAD CENTER APPLICATIONS FOR PHOTOVOLTAIC ELECTRICITY
 - COMPLETE DATA COLLECTION
 - CONDUCT FORMAL SCREENING OF POTENTIAL APPLICATIONS, IDENTIFY PREFERRED CANDIDATES
 - BEGIN ANALYSIS OF PREFERRED CANDIDATES
- TASK 3: INCENTIVE STRATEGIES FOR THE PHOTOVOLTAIC PROGRAM
 - FINISH ADAPTATION OF UTILITY FINANCIAL PLANNING MODEL TO GENERAL COMMERCIAL AND INDUSTRIAL ENTERPRISES
 - BEGIN EVALUATION OF INCENTIVES FOR USER-OWNED COMMERCIAL AND INDUSTRIAL PHOTOVOLTAIC SYSTEMS

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