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FINAL REPORT: MISSION ANALYSIS OF PHOTOVOLTAIC SOLAR ENERGY SYSTEMS

VOLUME I: SUMMARY

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FOR THE NATIONAL SCIENCE FOUNDATION/
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THE AEROSPACE CORPORATION

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Aerospace Report No.
ATR-76(7476-01)-1
Vol I

MISSION ANALYSIS OF PHOTOVOLTAIC SOLAR ENERGY SYSTEMS. ###

FINAL REPORT, ###

VOLUME I. ##

SUMMARY

1 December 1975

Prepared by
Energy and Transportation Division
THE AEROSPACE CORPORATION
El Segundo, California

Prepared with the Support of the
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FOREWORD

This report presents a summary of the results that were achieved under Grant No. GI-44099, "Mission Analysis of Photovoltaic Solar Energy Systems", issued by the National Science Foundation (NSF)/Research Applied to National Needs. The report is the first of three volumes; the others are: Volume II, Technical Report, and Volume III, Appendices.

The study was conducted by the Energy Programs Group of the Energy and Transportation Division of The Aerospace Corporation. Dr. Tapan Mukherjee has been the NSF Program Manager for this grant; the principal active supervision has been provided by Dr. Morton Prince (Chief, Photovoltaic Branch) and Dr. Leonard Magid of the Solar Energy Division of the Energy Research and Development Administration. Dr. A. B. Greenberg, General Manager of the Energy and Transportation Division, was the

Principal Investigator. Dr. M. B. Watson is Associate Group Director of the Energy Programs Group. Dr. S. L. Leonard, Director, Photovoltaic Office, provided the program management.

This report was prepared by Dr. S. L. Leonard.

The author of this report wishes to express appreciation for the support to the project by a number of other personnel of The Aerospace Corporation. These include Mr. E. Blond, Mr. A. Forster, Dr. R. T. Hall, Mr. W. A. Kammer, Mr. J. R. Kettler, Mr. H. J. Killian, Mr. D. E. Kind, Mr. R. B. Laube, Mr. O. J. Mead, Mrs. P. L. Merryman, Mr. J. A. Neiss, Dr. P. J. Peters, Dr. C. M. Randall, Mr. S. Sugihara, Ms. H. Wong, and Mr. E. K. Wright. The help of Mr. Fred Eggers in overseeing the production of the report and of Mrs. Janet Rausch in typing the text is also gratefully acknowledged.

ABSTRACT

This volume contains a summary report of a study program whose principal objective was to develop methods for the technical and economic evaluation of potential missions (applications) for photovoltaic solar energy conversion in the southwestern United States in the 1980-2000 period. A secondary objective was to apply the methodology, when developed, to the evaluation of a number of illustrative examples of candidate missions in order to obtain at least a preliminary indication of the competitive position of the photovoltaic technology in the future energy economy of the Southwest.

The general approach that was adopted was a conservative one in which photovoltaic solar energy conversion is treated, without favoritism, as just one more competitor in an energy market place that is characterized by high standards of service reliability and by various types of built-in subsidies (overt and hidden) for more conventional power generation methods. This approach therefore represents a "worst case" analysis in the sense that most of the reasonable modifications that might be made in the assumptions or methodology would probably be more favorable to photovoltaic technology. The results

that were obtained when this methodology was applied to various illustrative examples (indicating that, for array prices in the \$100-200/kWpk range, solar energy conversion can be competitive in at least two major classes of applications) are therefore conservative.

Because of their large potential significance, most of the effort in the study was devoted to two main classes of missions: on-site applications (in which the photovoltaic system serves an electric load point that is colocated with the system) and central station power plant applications. A smaller amount of attention was given to the electrolytic production of hydrogen with electric power generated by the photovoltaic conversion of solar energy.

The central element of the methodology that was developed is computer simulation of the performance of the photovoltaic system within the constraints that characterize the mission. The mathematical models and computer programs required for these simulations were constructed, and suitable representations were prepared for the solar energy (insolation) input and for the electric demand to be met. Included in the methodology was a

reliability analysis procedure for calculating the amount of conventional generation capacity that must be provided as a backup to the photovoltaic systems because of the intermittent availability of solar energy. Appropriate procedures for the economic analysis of missions in the three main classes were also formulated; the results of the performance computations (including the backup capacity requirements) and estimates of subsystem costs are the principal required inputs.

The methodology was applied to the evaluation of a number of specific examples of on-site and central station missions.

In the case of on-site missions, a fairly detailed technical and economic analysis was made of a baseline mission in which flat plate photovoltaic arrays were presumed to be deployed on single-family residences in Phoenix, Arizona. The effects on system performance of varying collector area, electric storage capacity, and collector orientation were studied in a systematic fashion. A number of sensitivity studies were also made, with the baseline mission as reference.

The central station power plant analyses that were carried out considered 100 MW plants of a single basic design that utilizes flat plate collectors whose

tilt angle (about an east-west axis) is adjusted monthly for optimum energy collection. The fundamental system parameters, array area and storage capacity, were varied systematically in studies of the effects of these parameters on system performance. For different ranges of these variables, the plant operation can be characterized as baseload, intermediate, or peaking.

Preliminary evaluation of the photovoltaic/electrolytic hydrogen production mission revealed that this is currently an unpromising application for the photovoltaic technology; therefore, the analysis was not carried further.

Representative results of the analyses that were made of on-site and central station missions are presented in the accompanying chart (page vii). These results, and others that are summarized in the body of this report, support the tentative conclusion that, with presently achievable efficiencies and with array prices in the \$100-200 kWpk range, photovoltaic solar energy conversion would indeed be competitive with alternative sources of energy. The analyses leading to this conclusion, furthermore, did not take into account a number of factors that might improve the competitive position of the photovoltaic technology, such as: a) the productive utilization of the thermal energy removed in cooling the cells, b) the use of concentrators,

c) relaxation of the current rigid standards for reliability of service, or
d) introduction of government incentives to encourage the use of solar energy or to compensate for noninternalized societal costs of conventional power production.

Mission Analysis of Photovoltaic Solar Energy Systems

REPRESENTATIVE RESULTS

ALL COSTS AND PRICES EXPRESSED IN 1975 DOLLARS

APPLICATION	SPECIFICATIONS		RESULTS OF ANALYSIS	
ON-SITE RESIDENTIAL SYSTEM PHOENIX, ARIZONA 1990	PEAK DEMAND	8.2 kW	ENERGY DISPLACEMENT	60.7%
	AVERAGE DEMAND	3.5 kW	REQUIRED CONVENTIONAL	
	ARRAY AREA	114.1 m ²	BACKUP CAPACITY	2.1 kW
	STORAGE CAPACITY	28.5 kWh	BREAKEVEN PHOTOVOLTAIC	
	COLLECTOR TYPE	FLAT PLATE, FIXED TILT	ARRAY COST	134.6 \$/kWpk
CENTRAL STATION POWER PLANT (Intermediate Mode) INYOKERN, CALIF 1990	RATED OUTPUT	100 MW	PLANT CAPACITY FACTOR	0.41
	ARRAY AREA	2(10 ⁶) m ²	REQUIRED BACKUP	
	STORAGE CAPACITY	0.5(10 ⁶) kWh	CAPACITY	25.8 MW
	COLLECTOR TYPE	FLAT PLATE, TILT ADJUSTED MONTHLY	PHOTOVOLTAIC ARRAY PRICE	100.0 \$/kWpk
			PLANT INVESTMENT COST	1125.7 \$/kW
CENTRAL STATION POWER PLANT (Baseload) INYOKERN, CALIF 1990	RATED OUTPUT	100 MW	BUSBAR ENERGY COST	40.4 mills/kWh
	ARRAY AREA	5(10 ⁶) m ²	PLANT CAPACITY FACTOR	0.81
	STORAGE CAPACITY	1.5(10 ⁶) kWh	REQUIRED BACKUP	
	COLLECTOR TYPE	FLAT PLATE, TILT ADJUSTED MONTHLY	CAPACITY	3.0 MW
			PHOTOVOLTAIC ARRAY PRICE	100.0 \$/kWpk
			PLANT INVESTMENT COST	2772.2 \$/kW
			BUSBAR ENERGY COST	46.1 mills/kWh

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I. INTRODUCTION

This section contains a discussion of the basic objectives and scope of the study and a description of the general approach that has been used for the technical and economic analysis of potential missions (applications) for photovoltaic solar energy conversion.

STUDY OBJECTIVES AND SCOPE

The main objectives of this study and the scope of the program are listed in Chart 1. The principal task was to develop methods for the technical and economic evaluation of three main classes of missions for the photovoltaic conversion of solar energy: on-site power generation, central station power generation, and fuel/feedstock production. A fourth mission class, special purpose applications, was to be examined if time and resources permitted.

On-site applications, in the terminology of this study, are those in which the photovoltaic system is dedicated to meeting all or part of the electric power demand at a load point that is colocated with the system. Examples of such applications might range from the use of a rooftop array to generate power for a single-family dwelling to the deployment of many acres of arrays to generate electricity for an industrial plant. Central station missions are those in which a large photovoltaic power plant generates electricity that is dispatched into the transmission/distribution system of an electric utility system. A fuel/feedstock production mission is one in which photovoltaic electricity is used in the direct production of a material

that can be used as a fuel or can serve as a manufacturing feedstock. The most obvious example, and the only one considered in this study, is the production of hydrogen by the electrolysis of water.

The second major task was to apply the evaluation methodology, when developed, to a number of illustrative examples of each of the principal mission classes. The purpose of these illustrative evaluations was twofold: to demonstrate and validate the methodology and to make a preliminary identification of the applications in which the potential photovoltaic contribution to meeting national energy needs is greatest. In order to narrow the geographic coverage and to permit analysis of regional problems, the specific applications that were studied were to be considered to be located in the southwestern United States and to take place in the 1980-2000 period. This mission evaluation task also included the assignment of technical and economic goals to be met by photovoltaic systems, subsystems, and components in order that photovoltaic technology can compete successfully with alternative ways of meeting the energy demands of each mission.

Study Objectives and Scope

**DEVELOP PROCEDURES FOR EVALUATING CANDIDATE PHOTOVOLTAIC SYSTEMS
AS APPLIED IN ALTERNATIVE MISSIONS**

**ASSESS ALTERNATIVE MISSIONS FOR PHOTOVOLTAIC SYSTEMS AND IDENTIFY
THOSE OF GREATEST POTENTIAL**

- **FOUR SPECIFIC MISSION CLASSES**
 - ON-SITE (supplemental) POWER**
 - CENTRAL STATION POWER**
 - FUEL/FEEDSTOCK PRODUCTION**
 - SPECIAL PURPOSE APPLICATIONS**
- **GEOGRAPHICAL AREA - SOUTHWESTERN U.S.**
- **TIME PERIOD - 1980-2000**

**ESTABLISH TECHNICAL AND ECONOMIC GOALS FOR SYSTEM, SUBSYSTEM, AND
COMPONENT DESIGN AND PERFORMANCE**

**DETERMINE THE MARKET CAPTURE POTENTIAL AND IMPACT ON RESOURCES
OF THE PREFERRED PHOTOVOLTAIC CONVERSION MISSION(S)**

Chart 1

GENERAL ANALYTICAL APPROACH

The procedures developed in this study for evaluating photovoltaic applications are all based on the general approach illustrated in Chart 2. It contains three basic elements: a) computer simulation of the performance of the photovoltaic system within mission constraints, b) reliability analysis to determine how much conventional generation capacity must be provided as backup, and c) economic analysis to determine the cost of providing mission power by photovoltaic means. This cost must then be compared with the cost of generating the required power by conventional methods.

The system simulation computations utilize a suitable model for the photovoltaic system, along with representations for the insolation input (characteristic of the geographical location) and for the electric power demand that characterizes the specific mission under study. These performance computations are carried out for a full year of simulated operation and the results serve as inputs both to the reliability analysis and the economic analysis.

The reliability analysis methodology reflects the assumption that a photo-

voltaic system will be required to meet the same reliability standards as would be imposed on an alternative energy source. Because of the variability of solar energy (and the high cost of energy storage), this reliability requirement implies the necessity for a backup source of power. In this study, it has been assumed that the required backup power will be provided by conventional generating plants via the transmission/distribution grid of a utility system. The reliability analysis determines the amount of additional conventional capacity that must be provided in order to ensure that the utility system can provide the needed solar backup without reducing the overall reliability of service. The capital cost of this additional backup capacity is part of the cost of providing photovoltaic power and is therefore one of the inputs to the economic analysis.

The economic analysis, in addition to providing photovoltaic power costs for comparison with the cost of conventional power, also provides estimates of the economic requirements (e.g., array cost goals) that must be satisfied if photovoltaic power production is to be economically competitive.

General Analytical Approach

Chart 2

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II. INSOLATION

This section contains a discussion of the insolation representations that have been constructed for use in simulation computations of the performance of solar energy conversion systems at various geographical locations. Also included are descriptions of two special studies: a) an analysis of the effect on solar cell output of variations in the insolation spectrum caused by atmospheric scattering and absorption and b) an investigation of the accuracy of insolation forecasting on the basis of forecasts of cloud cover.

INSOLATION DATA BASE

In the computer simulation of the performance of any solar energy conversion system, one of the principal inputs is a suitable representation for the insolation at the location of the system. The insolation representations needed for this study were, for the most part, already available as parts of a comprehensive insolation data base that has been developed at The Aerospace Corporation in the course of a succession of Solar Thermal Mission Analysis programs (References 1-3). The current contents of this data base, including additions that were made as part of this study, are illustrated in Chart 3.

The contributions made by the current study to this data base were a) the addition of three sites (Great Falls, MT; Charleston, SC; and Cleveland, OH); and b) the insertion of nighttime surface weather data into the records for six other sites (Albuquerque, NM; Phoenix, AZ; Omaha, NE; Blue Hill, MA; Sterling, VA; and Miami, FL).

As is indicated in the chart, the data base now contains two full years of hourly values for both direct (unscattered) insolation and total (direct plus scattered) insolation at 33 different sites. The total insolation data for 26 of these sites are measured values as recorded by the National Weather Service (NWS). For the remaining seven sites, total insolation values were estimated on the basis of a correlation that had been shown to exist between total insolation and NWS observations of opaque sky cover. Direct insolation measurements were available for only five of the sites. In all other cases, the values for this quantity were estimated on the basis of a correlation between direct and total insolation.

In addition to insolation data, the data base also contains information about a number of other weather variables that may be important to the operation of solar energy conversion systems. In a number of cases, however, these data are included only for daylight hours.

INSOLATION DATA BASE

- HOURLY DATA
 - TOTAL INSOLATION
 - DIRECT INSOLATION
 - CLOUD COVER
 - SELECTED WEATHER DATA
- TWO-YEAR RECORD
 - 1962, 1963
- U.S. CLIMATIC REGIONS REPRESENTED
 - DATA FOR 33 SITES AVAILABLE
(as of 1 October 1975)
- ESTIMATION PROCEDURES USED TO FILL GAPS IN RECORD

CALCULATED INSOLATION SPECTRUM AND SILICON SOLAR CELL OUTPUT - CLEAR DAY

The insolation data base illustrated in Chart 3 contains no information about the spectral content of the insolation. Its use in evaluating photovoltaic systems might therefore be questioned, because a) the response of photovoltaic devices depends markedly on the spectral distribution of the incident light and b) the spectrum of insolation at the earth's surface varies with time of day and with meteorological conditions as a result of atmospheric absorption and scattering.

For these reasons, an assessment of the effect on solar cell output of such spectral variations was carried out with the aid of a computer program for determining atmospheric transmittance as a function of wavelength and of the zenith angle of the source. When the spectrum of the extraterrestrial radiation is used as an input to this program, the output is the insolation spectrum at the surface of the earth. The program permits the use of one of five different standard models (Reference 4) of the atmosphere: a tropical model and models representing mid-latitude summer, mid-latitude winter, subarctic summer, and subarctic winter. All of these models incorporate the same size distribution for aerosol particles and

yield the same sea level visibility, 23 km. The models differ primarily in temperature and density profiles as well as in the water vapor content.

The curve labeled "insolation" on the right-hand side of Chart 4 is an example of one such calculated insolation spectrum. The atmospheric model used in this case was the tropical model, in which the total amount of precipitable water vapor is 5.2 gm/cm^2 , and the zenith angle of the sun was 0° . The corresponding curve on the left-hand side is the insolation spectrum obtained when the amount of precipitable water vapor in the tropical model is arbitrarily set to zero. A comparison of these curves reveals that absorption by water vapor plays a major role in shifting the surface insolation spectrum.

Also shown in Chart 4 are a standard spectral response curve for a silicon solar cell and curves obtained by convolving the calculated insolation spectra with the response curve. The integral with respect to wavelength of such a convolution spectrum, properly normalized, represents a calculated value for the electrical output of the solar cell.

Calculated Insolation Spectrum and Silicon Solar Cell Output

- CLEAR DAY -

VISIBILITY 23 km

CALCULATED INSOLATION SPECTRUM AND SILICON SOLAR CELL OUTPUT - HAZY DAY

Each of the atmospheric models mentioned in the discussion of Chart 4 is also available in an alternative version in which the aerosol concentration near the surface is increased in such a way as to reduce surface visibility to 5 km. When this hazy-day version of the tropical model is used to compute the insolation

spectrum at the surface (for a solar zenith angle, θ , of 0°), the curves in Chart 5 are obtained. Calculated solar cell output curves are also shown. (More precisely, it is the integral with respect to wavelength of these curves that represents a calculated value for solar cell output).

Calculated Insolation Spectrum and Silicon Solar Cell Output

- HAZY DAY -

VISIBILITY 5 km

Chart 5

EFFECT OF AIR MASS ON SILICON SOLAR CELL OUTPUT

Calculations of the type illustrated in Charts 4 and 5 were used in a systematic assessment of the magnitude of the error that might be introduced into simulation computations of photovoltaic system performance through neglecting the effect of variations in the spectral content of the insolation. Three of the available atmospheric models (tropical, mid-latitude summer, and mid-latitude winter) were used in both the high-visibility (23 km) and low-visibility (5 km) versions to compute ground-level insolation spectra. In each case, furthermore, calculations were carried out for six different zenith angles (0° , 15° , 30° , 45° , 60° , 70°). Each of the calculated spectra was convolved with the standard silicon solar cell spectral response curve and the resulting convolution spectra were integrated with respect to wavelength. The products of this procedure are proportional to calculated values for silicon solar cell output under 36 different sets of conditions. The results, normalized with respect to the result obtained at a zenith angle of 15 degrees with the high-visibility mid-latitude summer atmosphere, are shown in Chart 6 on the lines labeled "spectral effect included".

Each of the calculated insolation spectra was also convolved with the transmission curve for 1 mm of pyrex, and the resulting convolution spectra were also integrated with respect to wavelength in these cases. Each of the resulting values, when properly normalized, represents the total ground-level insolation as measured by a standard hemispherical pyranometer (which consists of a pyrex bulb enclosing an absorbing surface with a flat spectral response).

The ratio of the calculated solar cell output to the calculated pyranometer reading was then determined for the 15 degree zenith angle, 23 km visibility, mid-latitude summer case. This ratio was then used as a multiplying factor to convert all the calculated pyranometer readings into "spectral effect neglected" values for solar cell output. This computational procedure corresponds to the observational one in which the output of a solar cell is compared to the reading of a pyranometer on a clear summer day and then the observed "efficiency" factor is used to predict solar cell outputs from pyranometer readings made at other times.

Effect of Air Mass on Silicon Solar Cell Output

ATMOSPHERE	VISIBILITY	SPECTRAL EFFECT	ZENITH ANGLE					
			0	15°	30°	45°	60°	70°
MID-LATITUDE SUMMER	23 km	INCLUDED	1.0108	1.0	0.9642	0.8919	0.7511	0.5797
		NEGLECTED	1.0116	1.0	0.9626	0.8881	0.7477	0.5828
		DIFFERENCE	0.0008	0	-0.0016	-0.0038	-0.0034	0.0031
	5 km	INCLUDED	0.6174	0.6004	0.5469	0.4476	0.2878	0.1471
		NEGLECTED	0.6390	0.6222	0.5697	0.4728	0.3181	0.1793
		DIFFERENCE	0.0216	0.0218	0.0228	0.0252	0.0303	0.0322
MID-LATITUDE WINTER	23 km	INCLUDED	1.0339	1.0230	0.9873	0.9149	0.7733	0.5997
		NEGLECTED	1.0501	1.0387	1.0006	0.9255	0.7836	0.6153
		DIFFERENCE	0.0162	0.0157	0.0133	0.0106	0.0103	0.0156
	5 km	INCLUDED	0.6334	0.6163	0.5622	0.4612	0.2982	0.1540
		NEGLECTED	0.6678	0.6509	0.5971	0.4977	0.3379	0.1934
		DIFFERENCE	0.0344	0.0346	0.0349	0.0365	0.0397	0.0394
TROPICAL	23 km	INCLUDED	1.0041	0.9930	0.9575	0.8854	0.7458	0.5756
		NEGLECTED	1.0006	0.9892	0.9520	0.8776	0.7387	0.5751
		DIFFERENCE	-0.0035	-0.0038	-0.0055	-0.0078	-0.0071	-0.0005
	5 km	INCLUDED	0.6127	0.5957	0.5424	0.4436	0.2848	0.1454
		NEGLECTED	0.6304	0.6139	0.5619	0.4658	0.3124	0.1755
		DIFFERENCE	0.0177	0.0182	0.0195	0.0222	0.0276	0.0301

Chart 6

EFFECT OF AIR MASS ON SILICON SOLAR CELL OUTPUT

Some of the results that were presented in the preceding chart are displayed in graphical form in Chart 7. These curves represent the calculations for the tropical atmosphere case and therefore correspond to the spectral response curves shown in Charts 4 and 5.

The absolute differences between the "spectral effects included" and "spectral effects neglected" results shown in this and the preceding chart are small, although the percentage differences are

substantial for the hazy atmosphere cases at large zenith angles. The conclusion drawn from these results was that the errors incurred through neglecting the effect of variations in the insolation spectrum would not have a significant effect on the accuracy of the planned system simulation computations. Therefore, no attempt was made to develop methods for estimating the spectral distribution of the insolation on the basis of time of day or meteorological conditions.

Effect of Air Mass on Silicon Solar Cell Output

Chart 7

INSOLATION FORECASTING ACCURACY

It was recognized early in this study that important economic benefits might be derivable from the availability of accurate insolation forecasts to an operator of an on-site photovoltaic system. If he were warned in advance of an impending day of low insolation, for example, he might be able to extract the necessary backup energy from the utility grid during early morning off-peak hours and store it for use during the following day. Such a procedure would minimize the effect of the backup power requirement on peak demand in the utility system and therefore reduce the associated backup capacity requirement.

For this reason, a study was made of the potential accuracy with which insolation might be forecasted on the basis of the current state of weather forecasting practice. The results of this study are illustrated in Chart 8. Records of NWS forecasts of cloud cover for the year 1971 were used to infer hourly values for opaque sky cover at two different sites: Madison, WI, and Albuquerque, NM. From the opaque sky cover figures, values for

total insolation were calculated on the basis of a previously identified correlation between these variables. The hourly total insolation values determined in this way were summed to provide daily totals, which were then compared with measured daily total insolation data as presented in the NWS publication, "Climatological Data, National Summary". The central (white) portions of the bars in Chart 8 represent the fraction of the days (in each month) for which the "forecasted" insolation fell within $\pm 10\%$ of the measured value, while the remainder of each bar represents the fraction of the time that the forecast was too high or too low by more than 10%.

The results shown in Chart 8 for Madison (and the quite similar results that were obtained for Albuquerque) indicate that the ability to forecast insolation from present forecasts of cloud cover is quite limited. More accurate results, of course, might well be obtained if direct forecasts of insolation itself were prepared by trained meteorologists.

Insolation Forecasting Accuracy

- NWS CLOUD COVER FORECASTS USED TO INFER EXPECTED OPAQUE SKY COVER (tenths)
- INSOLATION FORECAST OBTAINED FROM KNOWN CORRELATION BETWEEN OPAQUE SKY COVER AND INSOLATION
- FORECASTED INSOLATION (daily total) COMPARED WITH MEASURED VALUES

Chart 8

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III. ELECTRIC POWER DEMAND

For simulation computations of photovoltaic system performance in a particular mission, an appropriate representation is required for the electric power demand that is characteristic of that mission. In this section, the development of such demand representations for both on-site and central station missions is described. Also included is some information about the projected density (per unit land area) of electric power consumption in residential, commercial, and industrial sections of an urban area in the southwestern United States.

DEMAND DATA REQUIREMENTS

In Chart 9 are listed the types of information that were needed in order to formulate demand representations for use in simulating the performance of photovoltaic systems in on-site and central station missions. The objective in both cases was to prepare a realistic and representative demand model that a) was expressed on the same hourly scale as are the insolation records, b) exhibited the diurnal and seasonal variations that are characteristic of the mission in the geographic region under study, and c) represented future (1980-2000) rather than current patterns.

Somewhat different approaches were used in developing the required demand representations for on-site and central station missions. In the on-site case, long-term records of hourly load point demand were not available and it was necessary to construct synthetic demand

"records" on the basis of representative daily profiles and data on seasonal variations in the different categories (residential, commercial, industrial) of energy consumption.

In the central station case, the demand that was of interest was the total demand in the utility system of which the solar plant was a part. The required demand representations, therefore, were based on projections into the future of long-term historical records of the demand in utility systems in the geographical region of interest. A projection methodology developed in The Aerospace Corporation Solar Thermal Mission Analysis Program (References 1 and 2) was used for this purpose.

The procedures used in constructing these demand models are illustrated in succeeding charts.

Demand Data Requirements

- ON-SITE APPLICATIONS (residential/commercial/industrial)
 - DAILY LOAD PROFILES
 - HOURLY
 - SEASONAL
 - SEASONAL ENERGY-DEMAND VARIATIONS
 - PROJECTIONS TO 1980-2000
 - LOAD PROFILE CHANGES
 - AVERAGE ENERGY DEMAND
 - CHANGES IN SEASONAL PATTERN
 - ENERGY DEMAND PER UNIT LAND AREA
- CENTRAL STATION PLANTS
 - LONG-TERM HISTORICAL RECORDS (hourly) OF SYSTEM DEMAND
 - SYSTEM DEMAND FORECASTS, 1980-2000

Chart 9

DEMAND REPRESENTATION - ARIZONA RESIDENTIAL

Chart 10 illustrates the method that was used in synthesizing a representation for the load point demand of an aggregation of single-family homes in Phoenix, Arizona. The basic ingredients are the summer and winter daily profiles shown in the graph on the left, considered to be representative of high-demand homes in this part of the Southwest, and the seasonal variations in Arizona residential demand, as displayed in the graph on the right. (The basic data for this latter graph were extracted from the Federal Power Commission publication, "Electric Power Statistics"; the long-term growth trend, assumed to be of exponential form, was removed by division.)

In synthesizing the demand representation in this case, the winter profile was taken to represent diurnal demand variations in January, February, March, November, and December. For the other months the summer profile was used. These profiles were multiplied by different factors for each month of the year; the multiplying factors were chosen

so that monthly energy consumption totals would display seasonal variations exactly matching the historical pattern.

The use of current daily profiles to simulate the profiles of the future was justified on the basis that the particular profiles selected for use represent energy consumption patterns that are expected to be more common in future years. The average annual energy consumption in the homes represented in the sample is about 30,000 kWh/year, presumably because they are equipped with appliances (e.g., central air-conditioning) that will be found to an increasing extent in the average home of the future, particularly in the Southwestern states.

A residential demand representation for Southern California was also prepared in the same way, the basis being some summer/winter diurnal profiles for high-demand homes in that region and the seasonal pattern of residential energy consumption in California.

Demand Representation - Arizona Residential

DAILY DEMAND PROFILES:
22 RESIDENCE SAMPLE,
HIGH-DEMAND HOMES
IN PHOENIX

MONTHLY ELECTRIC ENERGY CONSUMPTION
RESIDENTIAL SECTOR, ARIZONA
(Trend removed)

- ADOPT CURRENT DAILY PROFILE IN HIGH-DEMAND RESIDENTIAL SAMPLE AS REPRESENTATIVE PROFILE FOR 1990
- ADJUST DAILY TOTAL DEMAND TO MATCH OBSERVED SEASONAL VARIATION IN ARIZONA RESIDENTIAL DEMAND

Chart 10

REPRESENTATIVE COMMERCIAL AND INDUSTRIAL
DEMAND PROFILES - SOUTHWESTERN UNITED STATES

The methods described in the preceding chart were used in synthesizing a number of additional demand representations, among them representations for commercial and industrial load point demand. The graphs in Chart 11 illustrate some of the basic diurnal profiles that were used in constructing these demand models.

The commercial profiles in the chart represent two of the most important types of commercial establishment, supermarkets and department stores. In each case, the profiles are remarkably flat during store hours, dropping off to a much lower value after closing time. It is presumably the heavy refrigeration load in the supermarket case that prevents the off-hour demand from falling below about 50% of the daytime level. The striking similarity of the summer and winter demand curves reflects the fact that much of the heat input to such buildings is generated internally by various types of

equipment; the seasonal variation in air-conditioning load is therefore much smaller than in residences. Because of the basic similarity of the electrical loads in establishments of these types, the profiles shown in the chart are broadly representative.

Industrial daily demand profiles undoubtedly are substantially different for different industries and for different modes of operation. For many important industries, however, especially those that operate on a three-shift basis, the demand profile can be expected to be fairly constant over the full daily cycle, at least on the average. An example of the demand profile for one such industry, an electric-arc steel plant, is shown in the chart. While there are marked demand fluctuations as one or another of the furnaces is fired up or shut down, there is no regular daily pattern and no seasonal variation.

Representative Commercial and Industrial Daily Demand Profiles SOUTHWESTERN UNITED STATES

Chart 11

POWER DENSITY - SOUTHERN CALIFORNIA URBAN AVERAGES

In any assessment of on-site applications for photovoltaic solar energy conversion, it is important to know whether or not there will be sufficient solar energy falling on the site to permit meeting the expected demand for electric energy. In order to address this question, it is necessary to have information about the projected magnitude of demand per unit area of the site, since the solar energy supply will depend on the total area on which collectors can be deployed.

An indication of the demand per unit site area for different classes of electric energy use in one southwestern U.S. location is given by the numbers in Chart 12. The figures on peak loading represent projected values, for the years 1980 and 2000, for the peak demand per unit area (including public streets) in an urban sector of the service area of a Southern California utility company. (The letters L and H designate light and

heavy demand subgroups within the major category.) The values for average demand density were derived from the peak demand projections on the basis of reasonable assumptions about load factors and coincidence factors.

For comparison purposes, the average insolation per unit area and the average amount of power that could be produced by photovoltaic means are also shown.

The implications of these numbers are fairly clear. In general, site area limitations will not prevent photovoltaic systems from meeting all, or most, of the demand associated with single-family residences, small apartment buildings, or light commercial applications. In most other cases, photovoltaic systems will probably have to be viewed as supplementary sources, serving only a fraction of the full demand, even in favorable areas of the Southwest.

Power Density - Southern California Urban Averages

CLASS	DENSITY	PEAK LOADING (kW/mi ²)		AVERAGE DEMAND (kW/mi ²)	
		1980	2000	1980	2000
SINGLE-FAMILY	L	6,000	7,500	1,800	2,250
DWELLINGS	H	8,000	20,000	2,400	6,000
SMALL APARTMENT	L	30,000	45,000	9,000	13,500
BUILDINGS	H	60,000	90,000	18,000	27,000
LARGE APARTMENT	L	75,000	90,000	22,500	27,000
BUILDINGS	H	115,000	180,000	34,500	54,000
LIGHT COMMERCIAL	L	15,000	25,000	7,500	12,500
AREAS	H	35,000	90,000	17,500	45,000
HEAVY COMMERCIAL	L	40,000	75,000	20,000	37,500
AREAS	H	100,000	300,000	50,000	150,000
LIGHT INDUSTRIES		30,000	70,000	13,500	31,500
HEAVY INDUSTRIES		100,000	250,000	65,000	162,500

AVERAGE INSOLATION - SOUTHWESTERN U.S.

650,000 kW/mi²

CORRESPONDING AVERAGE PHOTOVOLTAIC

20,000 kW/mi²

POWER (Land use factor = 0.25, η = 0.12)

Chart 12

UTILITY SYSTEM DEMAND FORECASTING MODEL

The system demand models that were used in the central station power plant simulations in this study were developed by projecting into the future historical demand records for actual utility systems located in the geographical regions of interest. The basic input data for the projection methodology were long-term (up to 10 years) hourly records of total system demand.

The demand forecasting procedure that was used is illustrated in Chart 13. It is based on the assumption that a time series of values for electric power demand is a composite of several factors: a growth trend, variations induced by weather conditions, weekly and seasonal influences, and hourly cyclic variations. It has been assumed that the growth trend is exponential, that the seasonal and hourly variations are repeated from year to year, and that the effect of weather is random in the short run and follows some long-term cyclic pattern that cannot be quantized from available data without

a high degree of uncertainty. The forecasting procedure utilizes a decomposition methodology that attempts to separate these elemental factors from the historical demand record by the successive application of mathematical filters, each designed to extract specific demand components. The seasonal, weekly, and hourly factors isolated in this way are then combined with a forecasted value for peak demand to generate a demand record for a specific future year. In the decomposition/recomposition procedure actually used in this program, no attempt was made to include the effects of the more or less random variations in local weather.

This utility system demand forecasting methodology was developed in The Aerospace Corporation Solar Thermal Mission Analysis Program and is described more fully in the reports emanating from that program (References 1 and 2).

Utility System Demand Forecasting Model

TIME SERIES DECOMPOSITION AND RECOMPOSITION

Chart 13

UTILITY SYSTEM DEMAND PROJECTIONS - 1990

The procedure illustrated in the preceding chart was used to prepare two different utility system demand representations for use in this study. The waveforms in Chart 14 display the properties of these representations during three particular weeks in the year 1990.

The Southern California representation was generated by applying the projection methodology to historical records of demand in the Southern California Edison Company system. It should not be considered an actual forecast of demand in that particular system but rather as a reasonable indication of how the demand in a generalized large Southern California utility system might vary with time in 1990. The peak demand in this representation is 32,000 MW (occurring on

30 July 1990) and the minimum demand is 13,337 MW (on 1 April 1990). The system load factor (ratio of average to peak demand) is 0.65. The weeks that are represented in the figure are the standard weeks for Federal Power Commission (FPC) reporting purposes.

The central Arizona model is based on historical data from the Arizona Public Service Company but should be considered, again, as a generalized central Arizona demand projection rather than as a forecast for a particular company. In this case, the peak demand is 7109 MW (on 28 July 1990) and the minimum is 2227 MW (on 4 January 1990). The load factor is 0.56. The weeks represented in the waveform plots are not the standard FPC weeks but were chosen to include the peak demand.

Utility System Demand Projections 1990

Chart 14

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IV. SYSTEM SIMULATION AND RELIABILITY ANALYSIS METHODS

This section describes the methodology that was developed for the evaluation of the technical performance of photovoltaic systems in on-site, central station, and fuel production missions. This portion of the methodology includes a) simulation computations to determine system performance within mission constraints and b) reliability analysis to determine how much conventional capacity must be provided as backup for the photovoltaic systems.

PHOTOVOLTAIC SYSTEM SIMULATION MODEL

The basic system simulation model used in this study is illustrated in Chart 15. To facilitate adaptation of the model to different system configurations and different mission requirements, it was constructed in modular form, with careful attention to interfaces so that modules may be removed, inserted, or substituted with minimum disruptive effect. The blocks and flow paths indicated by solid lines represent the basic elements of the system. The dashed lines indicate elements needed if backup power is to be obtained from the utility grid during off-peak hours and stored for later use (on the basis, perhaps, of a forecast of cloudy weather). The dotted lines represent the power flow, if any, required for collector tracking and solar cell cooling.

The block labeled "insolation" represents an hour-by-hour record of direct (unscattered) insolation, total insolation, and various other weather information (including ambient temperature) at a particular site. The tracking routine applies the appropriate geometrical and tracking corrections for the alternative collector configurations analyzed. The collector routine defines the total collector area and the losses

associated with its design configuration (e.g., reflectivity, aiming losses, shading). The photovoltaic conversion routine represents the efficiency of the solar array as a function of temperature. A subroutine computes the solar cell temperature as a function of incident insolation and ambient temperature. The DC losses routine represents the internal resistive losses in the solar array and between the array and the power conditioning or electrical storage subsystems. The power conditioning routine represents the conversion of DC to AC power and any required AC voltage transformation needed to meet load requirements. The dashed power conditioning subsystem represents a rectifier for converting AC to DC, at the desired storage voltage, when conventional power is stored for later use. The electrical storage routine represents the performance of an electric battery with a maximum storage capability and representative internal losses.

The power requirements routine defines the electrical power required for solar cell cooling and collector tracking. The transmission losses routine represents the AC line losses between the power conditioning unit and the demand point.

Photovoltaic System Simulation Model

Chart 15

POWER PLANT DISPATCHING LOGIC

For application to central station missions, the basic system simulation model was modified through the incorporation of a dispatching logic designed to permit investigation of a range of operating strategies for a photovoltaic power plant.

The operation of the logic is illustrated in Chart 16. It is controlled by the values of two input parameters: PMULT, representing a prescribed fraction of the daily demand peak, and STBASE, a prescribed fraction of the total storage capacity. Solar plant output is dispatched into the utility system transmission/distribution grid only when either a) total system demand is greater than the product of PMULT and the peak system demand for the day or b) the stored energy exceeds the product of STBASE and the total storage capacity.

The effect of the operation of the logic is to dispatch solar power preferentially to meet a particular band of the total system demand. PMULT is chosen so that the annual amount of energy in the assigned band is some preselected fraction, f , of the nominal maximum annual energy output of the solar plant (i.e., the product of the rated output

and 8760, the number of hours in a year). If a plant provided only this in-band energy, its plant capacity factor, PCF, would be equal to f . The dispatch logic thus can constrain the solar plant, to a degree, to operate in base load (PCF ~ 1.0), intermediate (PCF ~ 0.5), or peaking (PCF ~ 0.1) mode.

The choice of STBASE modifies this strategy. If it is set high (~ 1.0), the system operates as described above, except that after the storage system has been filled, any additional solar power will be dispatched into the grid, regardless of the value of PMULT. For low values of STBASE, more of the solar output will be dispatched outside the assigned band, while for STBASE=0 solar power is dispatched whenever it is available (either directly from the array or from storage).

Parametric variation of these two input quantities permits the investigation of the effect of a variety of operating strategies on plant performance (as measured principally by the plant capacity factor), on requirements for backup capacity, and on the cost of the electric energy produced by the plant.

Power Plant Dispatching Logic

POWER IS DISPATCHED INTO
TRANSMISSION/DISTRIBUTION GRID
WHEN EITHER

- SYSTEM DEMAND EXCEEDS $(P_{MULT}) \times P_{MAX}$
- OR
- STORED ENERGY EXCEEDS
 $(STBASE) \times (STORAGE CAPACITY)$

Chart 16

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MARGIN ANALYSIS PROCEDURE

One of the basic guidelines in this study has been the requirement that the introduction of photovoltaic solar energy systems must not lead to a reduction in overall reliability of electric service, either to consumers served by photovoltaic systems or to others. One of the effects of this rule is that photovoltaic systems, because of the inherent variability of sunshine, need backup energy. If the backup energy comes from the conventional generation capacity of a utility system (as has been assumed in this study), the backup demand can add to peak demand in the utility system. The result is a reduction in overall reliability of service within the utility system unless additional generation capacity is added. The cost of the required additional capacity should then be included in calculations of the cost of photovoltaic energy. It is the function of the reliability analysis procedure to determine how much backup capacity is required in each case.

The two principal elements of the reliability analysis methodology are a) a model for the utility system, including a representation for the total system demand and a generation model (i.e., a

model for the generation capacity of the system, including the individual capacity, annual maintenance time requirement, and probability of unscheduled outage for each plant in the system) and b) a margin analysis procedure for calculating the statistical probability of loss of load (failure of the system to meet overall system demand). This latter element of the methodology is illustrated in Chart 17.

On the basis of the utility system generation model, separate computations are carried out for each month of the year (in order to account for variations in the number and type of plants that are "down" for scheduled maintenance) to determine the probability that the total available generation capacity of the system is less than a specified amount. One such curve is shown on the left in Chart 17. The loss of load computation is then carried out as indicated in the chart. For each hour of the year (and its associated system demand), the probability, P_i , that available capacity will be too small to meet demand is determined. The annual loss of load is the sum of these hourly P_i values.

For this study, baseline utility system models were developed for two systems, one representing Southern California and one representing central Arizona; the demand representations used were those illustrated in Chart 14. In each case, the generation model was adjusted (by optimizing maintenance schedules and adding additional capacity, as required) so that the annual loss of load was just under 2.4 hours per year, thereby satisfying the criterion that loss of load should not exceed one day in 10 years of service.

The determination of backup capacity requirements for photovoltaic systems was then a conceptually straightforward process. The baseline generation model was perturbed by the introduction of photovoltaic generation capacity, thereby changing the demand to be met by the conventional plants and, as a result, the annual loss of load. Incremental additions of conventional capacity were made to the generation model until the loss of load probability was restored to the original level. The amount of conventional capacity so introduced represented the required amount of backup capacity.

Margin Analysis Procedure

$$\text{ANNUAL LOSS OF LOAD} = \sum_{i=1}^{8760} P_i$$

Chart 17

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V. ECONOMIC EVALUATION PROCEDURES

In this section, descriptions are given of the procedures that were developed for analyzing the economics of on-site and central station photovoltaic missions.

The method selected for use in the economic analysis of on-site missions differed in several important respects from that used with central station missions. For the latter case, the chosen procedure involves a complete discounted cash flow analysis of the solar plant over its service lifetime, leading to a figure for the busbar cost (mills/kWh) of the electric energy produced. This cost figure can then be directly compared with the busbar cost of electric energy generated conventionally.

In the on-site case, however, the economic comparison of a photovoltaic system with more conventional generation methods is not so straightforward. The principal difficulty is that of assigning

a cost figure to the backup energy that is required in order to ensure reliable service. (Because the maximum power level of the backup service cannot be very different from what would be required in the absence of the photovoltaic systems, the capital cost of the distribution system would also be much the same in the two cases. In the photovoltaic case, however, this capital cost must be amortized through the sale of a much smaller amount of energy.) In order to circumvent the difficulty, an economic evaluation procedure was developed that is based on a determination of the present value cost of meeting the full load point demand over the lifetime of the photovoltaic systems. This cost is then compared with the present value cost of meeting the same demand by wholly conventional means. (Since the capital cost of distribution in the two cases is essentially the same, it cancels out of the computation.)

MISSION METHODOLOGY - ON-SITE

The procedure adopted for the economic evaluation of on-site missions is illustrated in Chart 18. It addresses a hypothetical situation in which a large number of new load points -- residential, commercial, industrial, or some mixture -- are simultaneously introduced into the service area of an existing utility system. The economic analysis is based on a comparison of the total cost of meeting this demand either a) by means of on-site photovoltaic arrays, backed up by the utility grid, or b) from the utility grid alone. The cost figures that are compared are total present-value costs (discounted to the year of introduction of the new demand) of meeting the new demand for the presumed 30-year lifetime of the photovoltaic systems. (New conventional generation capacity is assumed to have the same 30-year service life.)

When on-site photovoltaic systems are used, the only impact on the existing utility grid (represented in the analysis by one of the utility system models discussed in connection with Chart 17) is the incremental demand for backup power, D_B , as determined in simulation computations. In analyzing this case (Case 1), the backup demand is added, on an hour-by-hour basis, to the original

system demand to yield a new hourly demand record, $D_B + D_O$. The margin analysis procedure described in Chart 17 is used to determine how much conventional capacity must be added to the baseline generation model to restore the system loss of load to the original value. The total present value cost of meeting the new demand then includes a) the capital cost of the photovoltaic systems, b) the total investment cost (including interest during construction) of the backup capacity, c) the capital cost of additional long-line transmission facilities required in the case of a remotely located backup plant, d) the present value cost of operating and maintaining the photovoltaic systems, and e) the present value cost of the fuel and operation and maintenance charges that are allocatable to the backup energy.

The present value cost of meeting the new demand by conventional means (Case 2) is calculated in an exactly parallel fashion. The results of the two calculations are then used to determine the photovoltaic array cost for which the total present value costs are equal. This value is the array cost goal that must be met if the use of photovoltaic technology is to be economically competitive.

Mission Methodology – On - Site

Chart 18

POWER PLANT ECONOMIC MODEL FLOW CHART

The economic evaluation of central station missions was carried out with the aid of The Aerospace Corporation Power Plant Economic Model (Reference 5), originally developed for use in the Solar Thermal Mission Analysis studies. The Power Plant Economic Model is a computer program that carries out a complete discounted cash flow analysis of the entire economic life of an electric power plant, from the purchase of the site to the retirement of the plant from service.

A flow chart representing the operation of the Power Plant Economic Model is presented in Chart 19. The investment costs associated with plant construction are segregated into a number of different investment accounts representing different subsystems or investment categories. The initial input data to the model, therefore, are the capital investment costs for each of these accounts; these are estimated for a power plant of a given size in terms of base-year (e.g., 1975) dollars. To determine the corresponding costs for power plants of other sizes, an economics-of-scale subroutine has been included.

The effect of inflation is accounted for by a subroutine that determines the

escalation in costs from the base-year to the start of construction. During construction, cash flows are expended which incur interest-during-construction (IDC) expenses in addition to continued escalation of costs.

The base-year capital investment cost plus increments resulting from escalation and IDC determine the total capital investment cost at the year of commercial operation. This cost and the other fixed charges, such as insurance and property taxes, determine the total fixed charges.

Cash flows derived from pro forma income statements are discounted to the year of commercial operation. The rate of discount is the cost of capital typical of the utility industry and is based on a weighted average of the after-tax cost of common and preferred equity and long-term debt. Total cash outflows over the plant lifetime are determined by adding estimated operating costs to the fixed charges. The total busbar energy cost is determined by the requirement that discounted plant lifetime cash inflows and outflows be equal. The retail cost of energy can then be determined by adding in the per-kWh cost of transmission and distribution.

Power Plant Economic Model Flow Chart

Chart 19

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VI. ILLUSTRATIVE EXAMPLES: ON-SITE APPLICATIONS

This section contains descriptions of a number of illustrative examples of the application of the technical/economic evaluation methodology developed in this study to specific on-site missions for photovoltaic solar energy conversion. These analyses were carried out primarily to validate and demonstrate the methodology and only secondarily to provide preliminary indications of the competitive position of photovoltaic technology in this class of missions. They do not represent an exhaustive study of the many possible variations in mission or system characteristics or in external economic conditions; the results should therefore be considered indicative rather than definitive.

PHOTOVOLTAIC SYSTEM PERFORMANCE:
ON-SITE RESIDENTIAL APPLICATION

The on-site application that has received the most complete examination in this study is a baseline case in which individual photovoltaic systems are used to provide electric power to a large number of similar residences in Phoenix, Arizona. The results of one set of system simulation computations for this baseline case are displayed in carpet-plot format in Chart 20, where the energy displacement (fraction of total load point demand that is met by the photovoltaic systems) achieved is shown as a function both of array area and of storage capacity. The abscissa in the graph is not labeled because, in this format, it does not represent a specific variable but serves as a linear horizontal scale for interpolating between the curves that make up the quasi-three-dimensional surface in the figure.

The insolation representation used in these calculations was derived from the 1963 historical record for Phoenix. The demand representation used was the Arizona residential demand model illustrated in Chart 10; the average demand per residence in this case is 3.47 kW and the annual peak is 8.19 kW. In assessing the impact on the local utility

grid of the installation of these on-site photovoltaic systems, it was assumed that the total number of homes involved was approximately 35,000, corresponding to a total average power of 121.8 MW and a total peak power of 289 MW. The collectors were assumed to be flat plates, tilted about an east-west axis at an angle that was adjusted monthly for maximum total energy collection. The solar cell efficiency at 20°C was assumed to be 12.5%, and the array efficiency was 11.25% (array packing factor=0.9).

The graphs in Chart 20 illustrate the point that, for a given array area, increasing the storage capacity improves performance. The marginal advantage, however, decreases sharply after the storage capacity is so large that the array area can no longer consistently fill it. Similarly, the marginal advantage (for constant storage capacity) of increasing array area levels off when the storage capacity is no longer large enough to accommodate the excess power produced by the array. Points above the "knee" of the surface are thus clearly unfavorable from an economic point of view, since both arrays and storage capacity are costly.

Photovoltaic System Performance

ON-SITE RESIDENTIAL APPLICATION

LOCATION: PHOENIX, ARIZONA
DEMAND: ARIZONA RESIDENTIAL
COLLECTOR: FLAT PLATE, TILT

ADJUSTED MONTHLY
ARRAY EFFICIENCY (20°C): 0.1125

Chart 20

BACKUP CAPACITY REQUIREMENTS:
ON-SITE RESIDENTIAL APPLICATION

The reliability analysis methodology discussed earlier (in connection with Chart 17) was used to compute the amount of backup capacity required in most of the specific examples represented in the preceding chart (Chart 20).

For each example, three different hypothetical situations were examined; these are illustrated schematically in Chart 21. In Case 1, the utility system model used was the central Arizona model. The total average demand served by on-site photovoltaic systems in this case represented about 3% of the average demand of the entire utility system. Thus, on sunny days, there was about a 3% solar penetration of the system demand. In Cases 2 and 3, the utility system model was the Southern California model. In Case 2, the average on-site demand was taken to be 121.8 MW, as before, corresponding to a solar penetration of

approximately 0.6%. In Case 3, the system simulation results were all multiplied by a factor of 10, so that the solar penetration in this case was approximately 6%. For each case in Chart 21, two different incremental capacity figures are listed. The upper figure (for non-zero array area and storage) is the backup capacity that is required when the on-site demand is served by photovoltaic systems. The lower figure (for 0 array area and storage) represents the incremental capacity that would be required if the on-site demand were simply added to the total system demand, without photovoltaic systems to carry most of the added load.

These results, and similar ones for the other examples, are important inputs to the economic analysis, along with the results of the performance computations.

Backup Capacity Requirements

ON-SITE RESIDENTIAL APPLICATION

Chart 21

PHOTOVOLTAIC SYSTEM PERFORMANCE
AS A FUNCTION OF COLLECTOR TILT

In a second set of computations of system performance in the baseline residential application, it was assumed that the tilt angle of the array was fixed (as would be the case if the arrays were mounted directly on south-facing roofs with the assumed slope). The magnitude of the tilt angle was chosen to provide optimum performance in the mission, on the basis of preliminary performance computations for a range of values of the angle. (This procedure results in optimum matching of the tilt angle to the seasonal variations in both insolation and demand.) For these preliminary computations, the photovoltaic array area was taken to be 114 m² per residence (32.8 m²/kWav) and the electric storage capacity to be approximately 28.6 kWh per residence (8.2 hours at average power).

The results of these initial computations, shown in Chart 22, led to the selection of 24° as the fixed tilt angle to be used in the performance evaluation computations. The ordinate in the figure is the annual energy displacement, and the straight line across the top of the figure represents the energy displacement that could be achieved if the tilt angle were adjusted monthly for optimum energy collection, the operational strategy that is represented in Chart 20. The curve in Chart 22 indicates that, if the fixed tilt angle is properly chosen (matching the combined effects of insolation and demand), a level of system performance can be achieved that is less than 2% poorer than that obtainable when the tilt angle is adjusted monthly.

Photovoltaic System Performance

AS A FUNCTION OF COLLECTOR TILT

Chart 22

PHOTOVOLTAIC SYSTEM PERFORMANCE:
ON-SITE RESIDENTIAL APPLICATION

The carpet-plot surface in Chart 23 represents the system performance (as measured by the annual energy displacement) achievable under conditions that are identical to those represented in Chart 20 except that the south-facing flat plate collector has a fixed 24° tilt with respect to the horizontal. (In this

case, in order to minimize computational costs, the examples corresponding to the plateau area above the knee of the surface were omitted; these portions of the carpet plot do not represent attractive examples for economic analysis in any case.)

Photovoltaic System Performance

ON-SITE RESIDENTIAL APPLICATION

Chart 23

ENERGY FLOW IN RESIDENTIAL ON-SITE SYSTEM:
PERFECT INSOLATION/DEMAND FORECASTING

Fairly early in this study, it was recognized that the availability of accurate forecasts of insolation would make feasible operational strategies leading to significant reductions in the required amount of backup generation capacity. On the basis of a forecast of insufficient insolation, for example, the operator of a photovoltaic system could extract the necessary amount of backup energy from the utility grid during off-peak hours and store it for use during the following day. In this way, the impact of the backup energy requirement on the peak demand in the utility system could be minimized, with a consequent reduction in the required additional generation capacity. In order to investigate this possibility, an optional subroutine was developed, for inclusion in the system simulation program, that simulates in an approximate fashion the effect of very accurate insolation forecasting and the storage management strategy it makes possible.

In this optional subroutine, called the perfect forecasting option, the computer routine carries out two simulation computations for each 24-hour period. The

first computation obtains the information about insolation and demand during the succeeding 24 hours, computes the total required backup power, and makes this information available (as if forecasted) for the second computation. During the second simulation computation, this total amount of backup power (plus projected storage losses) is obtained from the grid during a preselected off-peak period (typically between 12 midnight and 7 am) and dispatched either to meet current demand or to storage, or both.

The flow of energy in the photovoltaic system when the perfect forecasting option is used is illustrated in Charts 24 and 25. The graphs in these charts show the hourly energy flows at the eight identified locations. The insolation representation used in this simulation was that for Phoenix in 1963, and the graphs cover a 48-hour period of operation on 24 and 25 April. The 24th was clear and sunny, but the following day was cloudy, with very low insolation. On the basis of the assumed perfect 24-hour forecast of insolation and demand, backup energy was obtained principally between midnight and 7 am, although the

Energy Flow in Residential On-Site System

PERFECT INSOLATION/DEMAND FORECASTING

INSOLATION: PHOENIX
DEMAND: ARIZONA RESIDENTIAL
COLLECTOR: FLAT PLATE,
24° FIXED TILT

Chart 24

finite size of the storage capacity (here taken to be 8.2 hours at average power) prevented perfect realization of this goal. It is clear from these graphs that the demand for backup energy has indeed been shifted away from the afternoon and evening hours to a very significant extent.

The upper two graphs in Chart 25 also illustrate another interesting point. When the storage management strategy considered here is applied, the result is a peak in the demand for backup power that can be even larger than the daytime peak in on-site demand. Alternatively, in the absence of forecasting, a sequence of cloudy days would quickly lead to a

situation where the early evening peak in load point demand is met entirely by backup power from the utility grid. In either case, therefore, with or without accurate insolation forecasting, the maximum backup power level is at least comparable to the maximum power level in the load point demand. The power rating in the distribution system used to bring in the backup power can therefore be no smaller than it would be if there were no photovoltaic system and the utility grid were meeting the entire load. It thus appears that, so long as the required backup power is obtained from the utility grid, the use of photovoltaic systems does not lead to appreciable savings in distribution costs.

Energy Flow in Residential On-Site System

PERFECT INSOLATION/DEMAND FORECASTING

INSOLATION: PHOENIX
 DEMAND: ARIZONA RESIDENTIAL
 COLLECTOR: FLAT PLATE, 24° FIXED TILT

Chart 25

EFFECT OF INSOLATION/DEMAND FORECASTING

An indication of the effect of the use of the perfect forecasting option on annual backup energy requirements and on the amount of required backup capacity can be obtained from the computational results shown in Chart 26. These results show that the required backup capacity can, indeed, be very appreciably reduced through the use of forecasting. A price is paid for this advantage, however, in the form of significant increases in the total requirement for backup energy. These increases are a result of the fact that, in the new mode of operation, a significant fraction of the backup energy

passes through the photovoltaic storage system enroute from the grid to the load point. In this process, input AC power is first rectified to DC and used to charge the storage batteries; it is later extracted from storage and inverted again to AC. In each of these steps, losses occur. As will be shown later in this report (Chart 33), the incremental cost of the additional backup energy substantially (and, in some cases, completely) offsets the economic gain arising from reduced backup capacity requirements.

Effect of Insolation/Demand Forecasting

PHOENIX RESIDENTIAL DEMAND/PHOENIX INSOLATION (1963)
 FLAT PLATE COLLECTOR, TILTED ABOUT EAST-WEST AXIS
 ARRAY EFFICIENCY (20°C): 0.1125

CASE 1. COLLECTOR TILT ADJUSTED MONTHLY
 SOUTHERN CALIFORNIA UTILITY SYSTEM AS BACKUP

ARRAY AREA		STORAGE CAPACITY		BACKUP ENERGY (10 ⁹ kWh)		BACKUP CAPACITY (MW)	
(10 ⁶ m ²)	(m ² /kWav)	(10 ⁶ kWh)	hr	NoF*	F**	NoF*	F**
6.0	49.3	1.5	12.3	0.175	0.238	4.0	0.019
8.0	65.7	1.5	12.3	0.118	0.142	1.8	0
60.0	49.3	15.0	12.3	1.750	2.386	150.0	4.7
80.0	65.7	15.0	12.3	1.179	1.418	58.0	0

CASE 2. COLLECTOR TILT FIXED AT 24°
 CENTRAL ARIZONA UTILITY SYSTEM AS BACKUP

4.0	32.8	1.0	8.2	0.407	0.553	73.3	9.1
6.0	49.3	1.0	8.2	0.282	0.393	29.3	1.1

* NoF = no insolation/demand forecasting

** F = perfect insolation/demand forecasting

Chart 26

EFFECT OF GEOGRAPHIC LOCATION

An indication of the sensitivity of the performance evaluation results discussed earlier in this section to geographic location was obtained through a set of simulation computations whose results are summarized in Chart 27. As is indicated in the figure, two different demand representations were used: the California residential demand model and the Arizona residential demand model that were discussed in connection with Chart 10. The insolation representation used in each case was derived from the 1963 historical records for the city in question. For all of these computations a flat plate collector of area $49.3 \text{ m}^2/\text{kWav}$ (approximately 170 m^2 per residence in the Arizona model, approximately 94 m^2 per residence in the California model) was assumed, with the tilt angle about an east-west axis adjusted monthly for optimum energy

collection. The storage capacity in each case corresponded to 8.2 hours of storage at average demand. The results displayed in the chart contain no surprises; the high insolation sites (Inyokern, Phoenix, Albuquerque, El Paso) show markedly better performance in both cases. The energy displacement at these sites is smaller for the Arizona model than for the California model simply because the very high summer peak in the Arizona model makes more severe demands on the output of the photovoltaic array; this summer demand peak is more pronounced than the summer peak in available insolation. Not surprising, either, is the relatively poor performance at Blue Hill, Massachusetts, although even at this obviously less favorable location for solar energy, the energy displacement is still only about 22% lower than at the most favorable location (El Paso).

Photovoltaic System Performance

ON-SITE RESIDENTIAL APPLICATIONS

EFFECT OF GEOGRAPHIC LOCATION

Chart 27

BASIC ASSUMPTIONS AND RESTRICTIONS IMPACTING ECONOMIC EVALUATIONS

The results of all the economic analyses described in this report, in Sections VII and VIII as well as in this section, are strongly dependent on a number of basic assumptions that have been made with respect to: a) system or subsystem design, b) subsystem performance

parameters, c) subsystem costs, and d) external conditions affecting mission requirements or economics. A listing of the assumptions and restrictions that apply, across the board, to the economic results generated in this study, is given in Chart 28.

Basic Assumptions and Restrictions Impacting Economic Evaluations

SYSTEM/SUBSYSTEM DESIGN

COLLECTOR TYPE: FLAT PLATE, TILTED ABOUT EAST-WEST AXIS

ENERGY UTILIZATION: ELECTRIC ENERGY ONLY; NO UTILIZATION OF THERMAL ENERGY
REMOVED FROM ARRAYS IN COOLING

SUBSYSTEM PERFORMANCE PARAMETERS

CELL EFFICIENCY: $\eta_C (20^\circ\text{C}) = 0.125$

ARRAY PACKING FACTOR: $f = 0.9$

ARRAY EFFICIENCY: $\eta_A (20^\circ\text{C}) = 0.9 (0.125) = 0.1125$

POWER CONDITIONING EFFICIENCY: $\eta_{PC} = 0.85$

STORAGE EFFICIENCY (overall): $\eta_{ES} = 0.70$

SYSTEM SERVICE LIFE: 30 YEARS

SUBSYSTEM COSTS (1975 Dollars)

ARRAY SUPPORT STRUCTURES

ON-SITE, ADJUSTABLE TILT: $\$10/\text{m}^2$

ON-SITE, FIXED TILT: $\$5/\text{m}^2$

CENTRAL STATION, ADJUSTABLE TILT: $\$15/\text{m}^2$

POWER CONDITIONING: $\$35/\text{kW}$

STORAGE: $\$20/\text{kWh}$

EXTERNAL CONDITIONS

RELIABILITY: UTILITY SYSTEMS LOSS OF LOAD NOT TO EXCEED ONE DAY IN 10 YEARS

GENERAL INFLATION RATE: 3%

INCENTIVES: NO GOVERNMENTAL INCENTIVES OR SUBSIDIES FOR SOLAR ENERGY

Chart 28

COST OF MEETING NEW RESIDENTIAL DEMAND

The approach used in evaluating on-site missions (as illustrated in Chart 18) is to compare the present value cost of meeting the electric power demand of a hypothetical group of load points either a) by conventional means or b) by means of on-site photovoltaic systems backed up by conventional capacity. A determination is then made of the photovoltaic array price that would equalize the two present value costs; this array price is identified as the goal that must be reached if photovoltaic technology is to be competitive in the application in question. The details of the calculation are displayed in Chart 29 for a typical case in which the collector was a flat plate whose tilt angle, about an east-west axis, was fixed at 24 degrees. The backup utility system was represented in these calculations by the central Arizona utility model (described on page 42). In the absence of photovoltaic systems, the required amount of additional capacity, as determined by margin analysis, was 267 MW, only a little smaller than the peak magnitude of the new demand (287 MW). When photovoltaic systems were assumed to be present, 73.3 MW of backup capacity was required (as shown in Chart 26). The assumed total array area was $4(10^6) \text{ m}^2$ (corresponding to $114 \text{ m}^2/\text{residence}$ or

$32.8 \text{ m}^2/\text{kWav}$) and the assumed value for storage capacity was 10^6 kWh (28.5 kW/residence or 8.2 hours at average demand).

In Chart 29, the price of photovoltaic arrays is initially taken to be unknown and is listed as $\$/\text{m}^2$; the total cost of a $4(10^6) \text{ m}^2$ array is then just $4X$ millions of dollars. The value of X is obtained by solving the equation constructed by setting the total present value costs for the two alternative energy sources equal to each other. The unit costs in the chart are given in 1990 dollars, but the resulting total costs are expressed both in 1990 dollars and in 1975 dollars.

The rationale for the unit cost figures for conventional power in these calculations is discussed in Sections 7.4 and 8.2 of Volume II of this report. The origins of the unit cost figures for the subsystems of the photovoltaic conversion system are also described in Section 8.2 of Volume II.

Note: The computations on which Chart 29 is based were governed by the basic assumptions and restrictions listed in Chart 28.

Cost of Meeting New Residential Demand

1990 PRESENT VALUE COSTS IN MILLIONS OF DOLLARS

New demand to be served: average, 121.8 MW; peak, 287 MW

Unit costs in 1990 dollars

	1990 DOLLARS	1975 DOLLARS
CONVENTIONAL ALTERNATIVE		
CAPITAL COST (coal plant, 267 MW at \$615/kW)	164.2	105.4
OPERATING COST		
FUEL (coal at 4.54 mills/kWh)	84.4	54.2
O&M (coal plant, \$15.97/kW)	36.5	23.4
TRANSMISSION (200 miles at \$450/MW-mile)	24.0	15.4
TOTAL	309.1	198.4
PHOTOVOLTAIC (flat plate collector, 24° fixed tilt)		
CAPITAL COST		
STORAGE (\$31.2/kWh)	31.2	20.0
POWER CONDITIONING (\$54.6/kW)	15.7	10.0
INSTALLATION/WIRING	10.9	7.0
ARRAY SUPPORT STRUCTURE (\$7.8/m ²)	31.2	20.0
ARRAY (\$X/m ²)		
PHOTOVOLTAIC O&M COST (2 mills/kWh)	24.9	16.0
BACKUP ENERGY		
FUEL (coal at 4.54 mills/kWh)	34.4	22.1
O&M (coal plant, \$15.97/kW)	14.9	9.6
BACKUP CAPACITY (coal plant, 73.3 MW at \$615/kW)	45.1	29.0
BACKUP TRANSMISSION (200 miles at \$450/MW-mile)	6.6	4.2
TOTAL	214.9 + 4X	137.9 + 4X
ARRAY PRICE } \$'m ²	23.6	15.2
GOAL, X } \$'kWpk	209.7	134.6

Chart 29

PHOTOVOLTAIC ARRAY PRICE GOALS:
RESIDENTIAL ON-SITE APPLICATION

Economic analyses like those outlined in Chart 29 have been carried out for most of the on-site application examples for which performance evaluations (including determination of the required backup capacity) had been made. The results of some of these analyses are summarized in Chart 30.

The examples illustrated in this chart are those whose performance characteristics are given in Chart 23. They represent the baseline residential application in Phoenix, Arizona, in which the tilt angle of the flat plate collector is fixed at 24° .

These results indicate that the use of photovoltaic technology in this type of on-site application can be economically competitive, even for currently available conversion efficiencies, if array prices in the \$100-200/kWpk (1975 dollars) can be achieved. This analysis, furthermore, has not taken into account the possible advantages associated with a) the productive use of the thermal energy that is removed from the arrays by cooling, b) the use of concentrators, c) any relaxation in the current rigid standards

for utility system reliability, or d) the introduction of economic incentives. The effect of any of these possibilities would be to increase, perhaps substantially, the array prices at which photovoltaic systems became competitive.

The results shown in Chart 30 support another interesting observation. The more cost effective examples appear to be those in which the array area is small and the storage capacity is either small or zero, even though the energy displacement in these cases is also small. In these cases, the solar energy system is used primarily to help the utility grid to meet the high daytime residential demand (much of it the result of air-conditioning). This observation suggests that it would be worthwhile to take a closer look than was possible in this study at applications where the photovoltaic system is only intended to meet part of the on-site demand.

Note: The computations on which Chart 30 is based were governed by the basic assumptions and restrictions listed in Chart 28.

Photovoltaic Array Price Goals

RESIDENTIAL ON-SITE APPLICATION

ARRAY AREA (10 ⁶ m ²)	STORAGE CAPACITY (10 ⁶ kWh)	ENERGY DISPL (10 ⁶ kWh)	SOUTHERN CALIFORNIA UTILITY			ARIZONA UTILITY		
			BACKUP CAPACITY (MW)	ARRAY PRICE GOAL (\$/kWpk)		BACKUP CAPACITY (MW)	ARRAY PRICE GOAL (\$/kWpk)	
				1990 Dollars	1975 Dollars		1990 Dollars	1975 Dollars
2.0	0	0.306	116.6	184.25	118.26	176.5	237.84	152.66
	1.0	0.340	83.3	148.50	95.32	168.9	121.60	78.05
4.0	0	0.420	75.3	127.98	82.15	107.3	198.50	127.40
	1.0	0.605 *	18.4	175.10	112.39	73.3	209.74	134.62 *
	1.5	0.619	18.4	139.70	89.66	73.3	174.34	111.90
6.0	0	0.457	60.7	77.46	49.72	79.2	138.57	88.94
	1.0	0.714	9.0	112.37	72.12	29.3	171.60	110.14
	1.5	0.791	9.0	96.55	61.97	29.2	155.88	100.05
8.0	1.0	0.741	7.8	66.99	43.00	15.1	121.59	78.04
	1.5	0.847	7.6	57.83	37.12	14.8	112.51	72.21
20.0	0	0.306	1440	182.71	117.27			
	10.0	0.340	1326	78.34	50.28			
40.0	0	0.420	1075	119.70	76.83			
	10.0	0.605	575	156.01	100.14			
	15.0	0.619	575	120.61	77.41			
60.0	0	0.457	951	69.63	44.69			
	10.0	0.714	218	127.11	81.58			
	15.0	0.791	217	111.39	71.49			
80.0	10.0	0.741	130	83.99	53.91			
	15.0	0.847	125	75.06	48.18			

* This example is the one cited in the Abstract as representative of on-site residential applications

Chart 30

PRESENT VALUE COST OF MEETING LOAD POINT RESIDENTIAL DEMAND:
DEPENDENCE ON FUEL COST

The sensitivity of the economic analyses of on-site missions to the cost of fuel for the backup power generation system is illustrated in Chart 31. The photovoltaic example represented here is the same example that is represented by Chart 29 (total array area $4 \times 10^6 \text{ m}^2$, total storage capacity $1.0 \times 10^6 \text{ kWh}$). This example is also included in Chart 30. The "coal-fired alternative" system is the same conventional alternative that was used as an economic reference point

in all of these economic analyses of on-site photovoltaic systems (as illustrated, for example, in Charts 29 and 30). The ordinate in the figure is the total present value cost (in 1990) of meeting the on-site residential demand represented by the Arizona residential demand model described in Chart 10. The straight-line graphs represent the dependence of this present value cost on fuel cost alone, assuming that all other variables remain unchanged.

Present-Value Cost of Meeting Load-Point Residential Demand

DEPENDENCE ON FUEL COST

Chart 31

ECONOMIC EFFECTS OF INSOLATION FORECASTING

The economic effect of the use of insolation forecasting (and the associated storage management strategy, as illustrated in Charts 24-26) is indicated by the figures in Chart 32. (These values correspond to Case 2 of Chart 26.) In the two cases displayed in the table, it is evident that the increases in backup energy costs offset to a considerable extent the reductions in backup capacity cost that are realized as a result of perfect forecasts of insolation. In the case where the array area is $6(10^6)\text{m}^2$, in fact, the economic advantage associated with forecasting is essentially eliminated. When it is

recognized that less than perfect forecasting would lead to appreciable energy wastage, and therefore to further reductions in the economic advantage produced by the availability of forecasts, it is clear that the economic value of even reasonably good forecasts in the operation of an on-site photovoltaic system would be fairly small (or, in many cases, zero).

Note: The computations on which Chart 32 is based were governed by the basic assumptions and restrictions listed in Chart 28.

Economic Effects of Insolation Forecasting

INSOLATION: PHOENIX 1963

DEMAND: ARIZONA RESIDENTIAL MODEL (121.8 MW average)

BACKUP UTILITY: CENTRAL ARIZONA MODEL

ARRAY TYPE: FLAT PLATE, FIXED 24° TILT

	NO FORECASTING		PERFECT FORECASTING	
ARRAY AREA (10^6 m^2)	4.0	6.0	4.0	6.0
STORAGE CAPACITY (10^6 kWh)	1.0	1.0	1.0	1.0
BACKUP CAPACITY REQUIRED (MW)	73.3	29.3	9.1	1.1
BACKUP POWER COSTS (millions of 1990 dollars)				
ENERGY (Fuel and O&M)	49.26	35.62	65.68	47.97
CAPACITY	45.08	18.02	5.60	0.68
TRANSMISSION	6.60	2.64	0.82	0.10
ARRAY PRICE GOALS (\$/kWpk)				
1990 Dollars	209.74	171.60	264.02	180.91
1975 Dollars	134.62	110.14	169.46	116.11

Chart 32

SAMPLE ECONOMIC SENSITIVITY CALCULATIONS

The sensitivity of the economic evaluation of one particular reference case to the assumed value of array efficiency and to the cost figures for power conditioning and storage is illustrated by the figures in Chart 33. The indicated 70°C efficiency of 16% corresponds to a room temperature (20°C) efficiency of 20%, a value that should be achievable within the next few years. Such high-efficiency cells, however, will undoubtedly be very expensive and the obstacles to reaching this efficiency

in low-cost (\$100-500/kWpk) arrays are formidable. The power conditioning and storage costs listed in Cases 3 and 4, respectively, of Chart 33 are each near the high end of the range of estimates of 1985-1990 costs for these subsystems when produced in large volume.

Note: The computations on which Chart 33 is based were governed by the basic assumptions and restrictions listed in Chart 28.

Sample Economic Sensitivity Calculations

INSOLATION: PHOENIX, 1963

DEMAND: ARIZONA RESIDENTIAL MODEL (121.8 MW average)

BACKUP UTILITY: CENTRAL ARIZONA MODEL

ARRAY TYPE: FLAT PLATE, 24° FIXED TILT

ARRAY AREA: $4.0 (10^6) \text{ m}^2$ ($\sim 114 \text{ m}^2$ / residence, 32.8 m^2 / kWav)

STORAGE CAPACITY: $1.0 (10^6) \text{ m}^2$ (~ 8.2 hours at average power)

		ARRAY PRICE GOALS (\$ / kWpk)	
		1990 Dollars	1975 Dollars
CASE 1.	BASELINE CONDITIONS	209.74	134.62
CASE 2.	$\eta(70^\circ) = 16\%$	235.72	151.30
CASE 3.	POWER CONDITIONING AT \$100/kW (1975 dollars)	145.11	93.14
CASE 4.	STORAGE AT \$50/kWh (1975 dollars)	105.87	67.95

Chart 33

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VII. ILLUSTRATIVE EXAMPLES: CENTRAL STATION MISSIONS

The mission evaluation methodology developed in this study was also applied to a limited number of examples of central station missions for photovoltaic solar energy conversion. As in the case of the on-site mission analyses described in the preceding section, these evaluations were carried out mainly to test and demonstrate the methodology and do not constitute a definitive analysis of this class of missions.

In all of the central station mission evaluations that are discussed in this section, the photovoltaic plant was taken to be a single 100 MW plant equipped with south-facing flat plate collectors, whose inclination about an east-west axis is adjusted monthly for maximum solar energy collection.

PHOTOVOLTAIC POWER PLANT PERFORMANCE:
INTERMEDIATE/BASELOAD OPERATION

As was indicated in the discussion of Chart 16, the first step in the evaluation of a photovoltaic power plant in this methodology is the adoption of a dispatching strategy through the selection of the input variables PMULT and STBASE. If baseload operation is to be evaluated, no computations are required: STBASE is set equal to 0 and the value of PMULT becomes irrelevant. To investigate the proper choices for intermediate mode operation, however, it was necessary to carry out a preliminary set of computations in which STBASE was varied from 0 to 1 while PMULT was held fixed at a value leading to an "in-band" plant capacity factor in the intermediate range. (The plant capacity factor is the ratio of the total annual energy output, in MWh, of a generating plant to the product of the rated plant capacity, in this case 100 MW, and the number of hours in a year, 8760.)

It was found that, even in this case, the lowest cost of photovoltaic power occurred for STBASE = 0. These results suggest that the preferred dispatching strategy for a 100 MW intermediate mode photovoltaic power plant is to dispatch power whenever it is physically possible as in baseload operation. Array size and

storage capacity will then determine whether the plant operates more like an intermediate mode plant or more like a baseload plant. The value of STBASE was therefore set equal to zero in the intermediate/baseload computations described in this section.

In Chart 34 are displayed the results of a set of simulation computations of the performance, as a function of array size and storage capacity, of a 100 MW photovoltaic power plant located at Inyokern, California. The insolation representation used in the calculations was based on 1963 data for Inyokern; the demand representation was the 1990 Southern California representation shown in Chart 14. The adopted measure of performance represented in the figure is the capacity factor, expressed either as a "solar capacity factor" or as a net plant capacity factor. The solar capacity factor, SCF, is the capacity factor that is computed if no allowance is made for scheduled maintenance outages. The net plant capacity factor, PCF, is obtained by multiplying the SCF value by 0.9 in order to correct for an assumed 10% scheduled downtime for planned maintenance procedures.

Photovoltaic Power Plant Performance

INTERMEDIATE/BASELOAD OPERATION

RATED PLANT CAPACITY: 100 MW

LOCATION: INYOKERN, CALIFORNIA

DEMAND: SOUTHERN CALIFORNIA

UTILITY SYSTEM MODEL, 1990

COLLECTOR: FLAT PLATE, TILT

ADJUSTED MONTHLY

ARRAY EFFICIENCY (20°C): 0.1125

Chart 34

PHOTOVOLTAIC POWER PLANT PERFORMANCE:
INTERMEDIATE/BASELOAD OPERATION

The computed performance of a 100 MW photovoltaic plant in Phoenix, Arizona, as a function of array size and storage capacity, is illustrated in Chart 35. As in the previous examples (Chart 34), the value of STBASE was set equal to zero so that the effective mode of operation of the plant (whether baseload or

intermediate) is determined by the size of the arrays and the storage subsystems. The differences between corresponding curves in Charts 34 and 35 are small, indicating that these two Southwestern sites are about equally favorable locations for a solar energy plant.

Photovoltaic Power Plant Performance

INTERMEDIATE/BASELOAD OPERATION

RATED PLANT CAPACITY: 100 MW

LOCATION: PHOENIX, ARIZONA

DEMAND: CENTRAL ARIZONA UTILITY

SYSTEM MODEL, 1990

COLLECTOR: FLAT PLATE, TILT

ADJUSTED MONTHLY

ARRAY EFFICIENCY (20°C): 0.1125

Chart 35

PHOTOVOLTAIC POWER PLANT PERFORMANCE:
PEAKING MODE

As another illustrative example, the operation of a 100 MW photovoltaic power plant in the peaking mode was investigated. It was assumed that the plant was located in the Southern California desert near Inyokern and was a part of the utility system represented by the Southern California model discussed in connection with Chart 17. For the purposes of this study, the peaking mode of operation was defined simply as one in which the plant capacity factor of the solar plant is in the range ($PCF=0.1-0.2$) characteristic of conventional peaking plants. It was left to the analysis itself to determine the extent to which a solar plant meeting this criterion actually functions like a peaking plant.

The procedure used in selecting appropriate values for PMULT and STBASE for peaking mode operation was the same as that described in connection with Chart 34. In this case, the value of PMULT was set so that the annual "in-band" plant capacity factor was 0.1. When STBASE was varied, it was found that the optimum value, in terms of the busbar cost of the electric energy produced, was approximately 0.4, and the value of

STBASE was therefore set equal to 0.4 in the computation runs discussed in this section. The dispatching strategy employed, therefore, is one in which the solar plant stores energy (up to 40% of the available capacity) early in the day for later dispatching at a time when the utility system demand is nearing its daily peak. The effect of this use of the storage is, of course, to reduce the peak demand to be met by the rest of the generation capacity of the utility system and therefore to increase the capacity displacement achieved by the solar plant (or, in other words, to reduce the amount of backup capacity required for the solar plant).

The results of the performance evaluations, for a range of values of array area and storage capacity, are presented in Chart 36. (There being no advantage to the carpet plot format in this case, a simpler parametric display was chosen.) These results, and the corresponding values for the required backup capacity (computed by the methods illustrated in Chart 17), were used in economic evaluations of these examples. The results are recorded in Chart 40.

Photovoltaic Power Plant Performance

PEAKING MODE

Chart 36

INVESTMENT COST BREAKDOWN (\$/kW):
PHOTOVOLTAIC POWER PLANT

As was reported in Section V, the economic evaluation of central station missions for photovoltaic solar energy conversion were carried out with the aid of a program (the Power Plant Economic Model illustrated in Chart 19) that makes a complete discounted cash flow analysis of plant construction and operation. In the course of its operation, this program computes the complete investment cost of the power plant, as of the year of initial commercial operation. Three representative examples of such investment cost estimates for photo-

voltaic power plants are shown in Chart 37. The dominant costs in these estimates are clearly those associated with the solar peculiar elements of the system: array support structure at \$15/m², photovoltaic arrays at \$11.25/m² (\$100/kWpk), power conditioning at \$35/kW, and electric storage at \$20/kWh.

Note: The computations on which these numbers are based were governed by the basic assumptions and restrictions listed in Chart 28.

Investment Cost Breakdown - \$/kW

PHOTOVOLTAIC POWER PLANT

	PEAKING	INTERMEDIATE	BASELOAD
ARRAY AREA (10^6 m^2)	1.0	2.0	5.0
STORAGE CAPACITY (10^6 kWh)	0.2	0.5	1.5
LAND	4.12	8.24	20.60
STRUCTURES, FACILITIES	10.85	10.85	10.85
ARRAY SUPPORT STRUCTURE	150.00	300.00	750.00
PHOTOVOLTAIC ARRAYS	112.50	225.00	562.50
POWER CONDITIONING EQUIPMENT	35.00	35.00	35.00
ELECTRIC STORAGE	40.00	100.00	300.00
ELECTRIC PLANT EQUIPMENT	24.49	39.46	107.83
MISCELLANEOUS PLANT EQUIPMENT	5.97	5.97	5.97
TOTAL BASIC PLANT COST	382.93	724.52	1792.75
CONTINGENCY ALLOWANCE	26.28	49.02	120.92
SPARE PARTS ALLOWANCE	2.32	4.52	11.26
INDIRECT COSTS	105.62	187.28	457.44
TOTAL CAPITAL INVESTMENT (1975)	517.15	965.34	2382.37
ESCALATION TO START OF CONSTRUCTION	185.04	339.20	832.21
TOTAL AT START OF CONSTRUCTION	702.19	1304.54	3214.58
INTEREST DURING CONSTRUCTION	133.64	250.57	617.38
ESCALATION DURING CONSTRUCTION	109.35	198.72	487.06
TOTAL COST AT YEAR OF COMMERCIAL OPERATION, 1990 DOLLARS	945.18	1753.83	4319.02
(1975 Dollars)	(606.66)	(1125.69)	(2772.16)

Chart 37

ECONOMIC RESULTS: PHOTOVOLTAIC POWER PLANT,
INTERMEDIATE/BASELOAD OPERATION

In Chart 38 are displayed the results of the economic evaluation of the 100 MW intermediate/baseload plants whose performance was illustrated in Chart 34. The backup capacity requirements listed in the table were determined on the basis of the methodology illustrated in Chart 17; the utility system model used in this calculation was the Southern California model that was discussed in connection with Chart 17.

These results are also displayed, in graphical form, in the next chart (Chart 39).

Note: The computations on which the values in this table are based were governed by the basic assumptions and restrictions listed in Chart 28.

Economic Results: Photovoltaic Power Plant, Intermediate/Baseload Operation

LOCATION: INYOKERN, CALIFORNIA

UTILITY SYSTEM MODEL: SOUTHERN CALIFORNIA MODEL

ARRAY AREA (10^6 m^2)	STORAGE CAPACITY (10^6 kWh)	PCF	BACKUP CAPACITY (MW)	INVESTMENT COST (\$/kW)		1991 BUSBAR ENERGY COST (mills/kWh)	
				1975 Dollars	1990 Dollars	1975 Dollars	1991 Dollars
1.0	0	0.220	76.1	523.75	816.00	45.83	73.56
	0.5	0.220	76.1	731.05	1138.98	58.04	93.15
	1.0	0.220	76.1	938.40	1462.03	70.27	112.78
	1.5	0.220	76.1	1145.78	1785.13	82.50	132.42
2.0	0	0.332	66.0	918.43	1430.92	44.83	71.96
	0.5	0.407	25.8	1125.69	1753.83	40.40	64.85
	1.0	0.407	25.8	1332.99	2076.80	47.02	75.47
	1.5	0.407	25.8	1540.32	2399.82	53.62	86.06
3.0	0	0.361	65.3	1321.40	2058.74	55.55	89.16
	0.5	0.506	6.7	1528.64	2381.62	41.70	66.93
	0.75	0.561	6.6	1632.27	2543.08	40.01	64.22
	1.0	0.570	6.6	1735.91	2704.54	41.74	66.99
4.0	1.5	0.570	6.6	1943.20	3027.51	46.46	74.57
	0.75	0.597	3.4	2044.0	3184.55	46.34	74.38
	1.0	0.665	3.4	2147.63	3346.00	43.61	70.00
	1.25	0.713	3.4	2251.26	3507.47	42.57	68.32
5.0	1.5	0.726	3.4	2354.90	3668.94	43.66	70.07
	0.75	0.610	3.2	2461.26	3834.65	54.16	86.93
	1.0	0.683	3.2	2564.89	3996.10	50.34	80.80
	1.25	0.754	3.2	2668.52	4157.55	47.38	76.04
	1.5	0.805	3.2	2772.16	4319.02	46.05	73.91

* These examples are those cited in the Abstract as representative of intermediate (upper example) and baseload (lower example) operation

Chart 38

BUSBAR ENERGY COST: PHOTOVOLTAIC POWER PLANT,
INTERMEDIATE/BASELOAD OPERATION

The economic evaluation results shown in the preceding chart are also displayed, in graphical form, in Chart 39. The broad crosshatched band in the figure represents the estimated range of projected 1991 costs of generating intermediate mode power in newly constructed conventional plants. The basis for the estimates represented by this band is discussed in Section 7.4 of Volume II of this report. The upper portions of the band, corresponding to busbar costs at which photovoltaic power would be competitive, represent recent fuel-cost projections based upon developments that have taken place since 1973. The graphs in Chart 39 indicate that a 100 MW photovoltaic plant with a total array area of approximately $2.5(10^6)\text{m}^2$ and about $0.5(10^6)\text{kWh}$ (5 hours) of storage capacity would provide power at the lowest cost, and that this cost would indeed be competitive with that associated with conventional intermediate mode plants. The carpet plot in Chart 34 indicates that such a

plant would have a plant capacity factor of about 0.46, a very appropriate value for an intermediate mode plant.

The results displayed in Charts 38 and 39 also indicate that, although photovoltaic power plants can operate as baseload plants (with plant capacity factors as high as 0.8), they would probably not be able to compete effectively with conventional baseload plants. Even when the projected 1991 busbar energy cost for a 1000 MW coal-fired baseload plant, as shown in Table 18 of Volume II of this report, is adjusted upward on the basis of the new coal price projections discussed at the end of Section 7.4 of that volume, the resultant figure is approximately 35 mills/kWh (1990 dollars), still well below the corresponding figures for photovoltaic power.

Note: The computations on which the values displayed in Chart 39 are based were governed by the basic assumptions and restrictions listed in Chart 28.

Busbar Energy Cost

PHOTOVOLTAIC POWER PLANT

INTERMEDIATE/BASELOAD OPERATION

Chart 39

ECONOMIC RESULTS: PHOTOVOLTAIC POWER PLANT,
PEAKING OPERATION

In Chart 40 are presented the results of economic analyses of the peaking mode examples whose plant capacity factor (PCF) values were presented in graphical form in Chart 36. These PCF factors are also listed in Chart 40, along with values for the "in-band" PCF. This latter parameter is the PCF value obtained if only power delivered into the assigned band is considered. (The assigned band is the 100 MW-wide portion of the total utility system demand that lies above the level defined by PMULT, as shown in Chart 16).

The 1991 busbar energy costs shown in Chart 40 compare quite favorably with the 99 mills/kWh busbar cost that has been projected (see Section 7.4 of Volume II of this report) for energy produced by

new (in 1990) gas turbine peaking plants. This comparison is probably not a legitimate one, however. As is indicated by the difference in the in-band and total plant capacity factors, these solar plants deliver considerably more of their power outside the assigned peaking band than within the band. This out-of-band power is really competing with conventional intermediate mode power (at 40-65 mills/kWh in 1991).

An attempt to make a more meaningful comparison is illustrated in the next chart (Chart 41).

Note: The computations on which the cost figures shown in Chart 40 are based were governed by the basic assumptions and restrictions listed in Chart 28.

Economic Results: Photovoltaic Power Plant, Peaking Operation

LOCATION: INYOKERN, CALIFORNIA

UTILITY SYSTEM MODEL: SOUTHERN CALIFORNIA MODEL

ARRAY AREA (10^6 m^2)	STORAGE CAPACITY (10^6 kWh)	PCF		BACKUP CAPACITY (MW)	INVESTMENT COST (\$/kW)		1991 BUSBAR ENERGY COST (mills/kWh)	
		TOTAL	IN BAND		1975 Dollars	1990 Dollars	1975 Dollars	1991 Dollars
0.5	0	0.110	0.013	91.3	330.89	515.52	72.93	117.05
	0.2	0.0989	0.038	65.2	413.82	644.73	84.64	135.84
	0.4	0.0904	0.059	41.3	496.77	773.97	97.06	155.78
	0.6	0.0856	0.070	28.8	579.72	903.21	111.01	178.17
1.0	0	0.220	0.026	76.1	523.75	816.00	45.83	73.56
	0.2	0.209	0.052	45.9	606.66	945.18	49.33	79.18
	0.4	0.201	0.072	27.9	689.59	1074.38	54.16	86.93
	0.6	0.195	0.083	19.1	772.52	1203.59	60.09	96.44
1.5	0	0.301	0.035	67.7	719.79	1121.44	41.10	65.97
	0.2	0.312	0.058	37.0	802.70	1250.60	40.36	64.78
	0.4	0.305	0.075	21.6	885.61	1379.78	43.39	69.64
	0.6	0.301	0.086	14.9	968.53	1508.97	46.92	75.31

Chart 40

COMPARISON OF 1991 BUSBAR COSTS FOR SOLAR ENERGY
(PEAKING PLANT) AND FOR COMPETITIVE CONVENTIONAL ENERGY

The busbar costs for energy from a photovoltaic power plant operated in quasi-peaking mode, as reported in the preceding chart (Chart 40), are not strictly comparable with the costs of energy from conventional peaking plants. Much of the energy from the photovoltaic plants in these examples was delivered outside the demand band associated with peaking power and is thus actually competing with conventional intermediate-mode power.

A more legitimate indication of the competitive position of solar power in these cases can be obtained by computing a composite figure for the cost of replacing the solar power in each case by conventional power. If, for example, it

is assumed that the cost of conventional power delivered to the assigned peaking band is 100 mills/kWh while power delivered outside the band costs 65 mills/kWh, the composite figures shown in Chart 41 are obtained. These numbers indicate that photovoltaic power is not competitive except for those cases when the array area is $1.5(10^6)\text{m}^2$. In these cases, however, the total plant capacity factor is approximately 0.3 and the plant is really functioning like one of the intermediate mode plants represented in Charts 39 and 40.

Note: The computations on which the cost figures in Chart 41 are based were governed by the basic assumptions and restrictions listed in Chart 28.

Comparison of 1991 Busbar Costs for Solar Energy (peaking plant) and for Competitive Conventional Energy

ARRAY AREA (10 ⁶ m ²)	STORAGE CAPACITY (10 ⁶ kWh)	PCF	1991 BUSBAR COST OF SOLAR ENERGY (mills/kWh)	COMPOSITE 1991 BUSBAR COST OF CONVENTIONAL ENERGY (mills/kWh)
0.5	0	0.110	117.05	69.14
	0.2	0.099	135.84	78.45
	0.4	0.090	155.78	87.84
	0.6	0.086	178.17	93.62
1.0	0	0.220	73.56	69.14
	0.2	0.209	79.18	73.71
	0.4	0.201	86.93	77.54
	0.6	0.195	96.44	79.90
1.5	0	0.301	65.97	69.07
	0.2	0.312	64.78	71.51
	0.4	0.305	69.64	73.61
	0.6	0.301	75.31	75.00

Chart 41

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VIII. ILLUSTRATIVE EXAMPLE: FUEL PRODUCTION

A very much briefer study than those reported in the preceding two sections was made of a third type of mission for the photovoltaic conversion of solar energy: the electrolytic production of hydrogen for use as a portable general purpose fuel. The specific application that was studied was one in which the electric power generated in the photovoltaic arrays of a large remotely-located plant is used solely for the production of hydrogen. The hydrogen, therefore, is not considered as a byproduct or solely as a medium for local energy storage but rather as a commercial product intended for wide distribution, in competition with portable fossil fuels.

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PHOTOVOLTAIC/ELECTROLYTIC HYDROGEN PRELIMINARY COST ESTIMATES

Chart 42 contains the elements of the relatively simple analytical procedure that was used to obtain preliminary cost estimates for photovoltaic/electrolytic hydrogen. The results are expressed in terms of 1975 dollars, in this case, to facilitate comparison with the unit costs of competitive fuels as estimated in a separate study that is illustrated in the next chart (Chart 43).

The analysis was carried out for an example in which a plant capable of producing a maximum of 1000 MW of photovoltaic power is located at Inyokern, California. A preliminary tradeoff analysis showed that the unit cost of the product would be smallest if the total electrolytic capacity, measured in terms of input electric power, were between 80% and 90% of the annual maximum in photovoltaic output (if the basic photovoltaic array cost is \$100/kWpk). Accordingly, the electrolytic capacity in the model was set at 900 MW; excess photovoltaic energy was assumed to be dissipated in some nonproductive fashion.

The indicated capital costs for the photovoltaic portion of the plant are

consistent with those used in the analysis of photovoltaic central station plants (Section VII). The figure for the electrolytic portion of the plant is based on cost estimates quoted in Reference 6 (\$48/kWe, of which 36% is allocated to a power supply that is not needed if photovoltaic power is used) for an "advanced system" capable of producing hydrogen at efficiencies yielding 0.050 lb/kWh.

The figure for the annual production of hydrogen is based on simulation computations which yielded a value of $2.40(10^9)$ kWh for the total (annual) amount of electric energy used in the electrolysis of water. At a presumed production efficiency of 0.05 lb of hydrogen per kWh of electric energy, somewhat better than the efficiency in currently available cells (Reference 6), the total annual production of hydrogen was therefore $1.2(10^8)$ pounds or $7.73(10^{12})$ Btu (at a conversion rate of 325 Btu per standard cubic foot).

The final estimate of the unit cost of the hydrogen produced in this way was obtained in a simple levelized fixed

charge calculation in which the fixed charge rate was assumed to be 16.5%. (This figure is based on fixed charge rates derived in The Aerospace Corporation Solar Thermal Mission Analysis Program (References 1 and 2) for evaluating solar thermal plants.) The annual operation and maintenance cost figures for the electrolytic plant were based on data from Reference 6.

The procedure illustrated in Chart 42 is clearly an approximate one. It is, however, sufficiently accurate to show that photovoltaic/electrolytic hydrogen (even when the photovoltaic array price is \$100/kWpk) is unlikely to be able to compete with any of a number of alternative fuels, as illustrated in the next chart (Chart 43).

Photovoltaic/Electrolytic Hydrogen

PRELIMINARY COST ESTIMATES

MAXIMUM ELECTRIC POWER: 1000 MW (~250 MWav)

ELECTROLYTIC PLANT MAXIMUM CAPACITY: 900 MWe

LOCATION: INYOKERN, CALIFORNIA

COLLECTORS: FLAT PLATE, TILT ADJUSTED MONTHLY, TOTAL AREA $8.24 (10^6) \text{ m}^2$

	COST (Millions of 1975 Dollars)
<u>INVESTMENT COST</u>	
PHOTOVOLTAIC PLANT	
LAND ACQUISITION	3.39
STRUCTURES (\$8/kWav)	2.00
ARRAY SUPPORT STRUCTURES (\$15/m ²)	123.60
PHOTOVOLTAIC ARRAYS (\$100/kWpk; \$11.25/m ²)	92.70
ELECTRIC AND MISC PLANT EQUIPMENT (\$20/kWav)	5.00
ELECTROLYTIC PLANT	<u>27.63</u>
TOTAL	254.32
CONTINGENCIES (7%)	17.80
SPARE PARTS (1%)	<u>2.54</u>
TOTAL DIRECT COST	274.66
INDIRECT COSTS (10% of Solar Equipment, 53% Otherwise)	52.56
INTEREST DURING CONSTRUCTION (16%)	<u>52.36</u>
TOTAL INVESTMENT COST (Year of Startup)	379.58
<u>UNIT COST OF PRODUCT (Levelized Fixed Charge Estimate)</u>	
ANNUAL PRODUCTION: $7.73 (10^{12}) \text{ Btu}$	
ANNUAL OPERATION AND MAINTENANCE COSTS	
PHOTOVOLTAIC PLANT (@ 2 mills/kWh): $4.8 (10^6)$	
ELECTROLYTIC PLANT (@ \$0.19/10 ⁶ Btu): $1.5 (10^6)$	
FIXED CHARGE RATE: 0.165	
UNIT PRODUCT COST:	$\frac{379.58(10^6)(0.165) + 4.8 (10^6) + 1.5 (10^6)}{7.73 (10^{12})} = \$8.91/10^6 \text{ Btu}$

Chart 42

PROJECTED UNIT FUEL PRICES

The graphs in Chart 43 present the results of an independent auxiliary study that was carried out to develop estimates of the future (1980-2000) costs of fuels that would be economic competitors of photovoltaic/electrolytic hydrogen. (This study is described in some detail in Appendix F of Volume III of this report). The principal message of Chart 43 is that there are a number of portable fossil fuels (those labeled "synthetics" in the figure) for which the projected 1990 cost is less than about $\$2/10^6$ Btu (in 1973 dollars) and that the projected 1990 cost of hydrogen itself, from several different sources, is less than $\$4/10^6$ Btu. Photovoltaic/electrolytic hydrogen, at approximately $\$9/10^6$ Btu, would not be able to compete.

While the estimates represented in both Charts 42 and 43 are subject to a number of uncertainties, the indicated price differentials between photovoltaic/electrolytic hydrogen and its competitors are believed to be appreciably greater than the combined uncertainties in the cost estimates.

It thus appears that, even for array costs of $\$100/\text{kWpk}$ (1975 dollars), the use of photovoltaic electricity to generate hydrogen for use as a general purpose fuel is not nearly so attractive an application for the technology as are either the on-site missions or the central station missions to which most of this study has been devoted.

Projected Unit Fuel Prices

CONSTANT 1973 DOLLARS

- SYNTHETICS {
- a - HI-Btu COAL GAS
 - b - COAL SYNCRUDE
 - c - LO-Btu COAL GAS
 - d - COAL METHANOL
 - e - SHALE GAS
 - f - SHALE SYNCRUDE

Chart 43

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IX. RESULTS AND CONCLUSIONS

This section contains a brief summary of the results that have been achieved in this program and a discussion of the tentative conclusions that have been reached.

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SUMMARY OF RESULTS

The results that have been achieved in this study are summarized in Chart 44. The principal achievements were:

1. Improvements were made in the available insolation data base and studies were made of the effect of spectral variations on photovoltaic system performance and of the probable accuracy of forecasts of insolation.

2. Suitable demand representations were prepared for use in simulating both on-site and central station missions in the southwestern United States in the 1980-2000 time period.

3. Procedures for evaluating the performance of photovoltaic systems in on-site, central station, and fuel production missions were formulated and implemented; this task included the preparation of a modular system simulation model and the adaptation of an available reliability analysis procedure to the photovoltaic case.

4. Methodology for the economic evaluation of on-site and central station missions was developed.

5. A number of illustrative examples of on-site missions were analyzed.

a. A detailed evaluation was made of a baseline residential application in Phoenix, Arizona; the results indicated that photovoltaic technology would be competitive, under the assumed conditions, for array prices in the \$100-200/kWpk range.

b. Studies were made of the sensitivity of the technical and economic evaluations to a number of different variables.

6. Several illustrative examples of central station missions were evaluated.

a. Performance analyses were made for 100 MW plants, with flat plate collectors, operating in intermediate/baseload and peaking modes.

b. Economic analyses were carried out for these examples; it was found that photovoltaic power plants operating in intermediate mode would be

economically competitive in 1990 for array prices in the \$100-200/kWpk range.

7. A limited study was made of the photovoltaic/electrolytic production of hydrogen, leading to the preliminary conclusion that the use of photovoltaic technology would not be competitive in this mission, at least in the period before the year 2000.

Summary of Results

- TECHNICAL/ECONOMIC EVALUATION PROCEDURES FOR ON-SITE AND CENTRAL STATION MISSIONS DEVELOPED, AND OPERATIONAL
 - INSOLATION REPRESENTATIONS
 - SPECTRAL EFFECTS
 - FORECASTING ACCURACY
 - DEMAND REPRESENTATIONS
 - SYSTEM SIMULATION MODEL
 - CAPACITY DISPLACEMENT METHODOLOGY
 - ECONOMIC EVALUATION METHODOLOGY
- ANALYSIS OF A LIMITED NUMBER OF ILLUSTRATIVE EXAMPLES COMPLETED
 - ON-SITE
 - BASELINE RESIDENTIAL SYSTEM, PHOENIX
 - PERFORMANCE SENSITIVITY TO
 - GEOGRAPHICAL LOCATION
 - DEGREE OF SOLAR PENETRATION
 - TYPE OF COLLECTOR, ORIENTATION
 - TYPE OF DEMAND PROFILE (commercial/industrial)
 - ECONOMIC SENSITIVITY TO
 - SUBSYSTEM COSTS
 - ARRAY EFFICIENCY
 - FUEL COST
 - INSOLATION FORECASTING
 - CENTRAL STATION
 - 100 MW PLANT
 - INTERMEDIATE MODE
 - PEAKING MODE
 - FUEL PRODUCTION
 - ELECTROLYTIC HYDROGEN PLANT (1000 MWe peak)

Chart 44

TENTATIVE CONCLUSIONS

The conclusions that have been reached on the basis of this study are summarized in Chart 45. The illustrative examples that were evaluated in the study (as described in Sections VI-VIII) were not intended to, and do not, constitute definitive studies of the missions involved. They do, however, provide at least preliminary indications of the competitive position of photovoltaic solar energy conversion in the missions examined, within the constraints that were applied in the analysis. These results suggest that:

1. On-site and central station missions are about equally attractive as future (1990) applications for photovoltaic solar energy conversion.

2. In both of these applications photovoltaic technology, for array prices

in the \$100-200/kWpk range and currently achievable array efficiencies, would be competitive with conventional alternatives even a) without the constructive utilization of the thermal energy removed in cooling the cells, b) without the use of concentrators, c) without reduction in utility system reliability, and d) without the introduction of incentives designed to encourage the use of solar energy.

3. The competitive position of the photovoltaic technology in either of these two classes of missions would be improved, perhaps substantially, by the relaxation in a realistic manner of the constraints imposed in the illustrative calculations carried out in this study.

Tentative Conclusions

- THE METHODOLOGY THAT HAS BEEN DEVELOPED FOR EVALUATING ALTERNATIVE MISSION CONCEPTS IS PRACTICAL, EFFECTIVE, AND READILY ADAPTABLE TO A VARIETY OF MISSIONS
 - MODULAR SYSTEM SIMULATION PROCEDURE DESIGNED TO INCORPORATE RESULTS OF SYSTEM DESIGN/ANALYSIS PROGRAMS AS AVAILABLE
 - EVALUATION OF BACKUP CAPACITY REQUIREMENT (interface with utility grid) INCLUDED
- VARIATIONS OF SPECTRAL CONTENT OF INSOLATION DO NOT SIGNIFICANTLY IMPACT MISSION/SYSTEM EVALUATIONS
- ON-SITE RESIDENTIAL APPLICATIONS AND CENTRAL STATION MISSIONS (intermediate mode) ARE EQUALLY PROMISING IN THE SOUTHWESTERN U.S.
 - MISSIONS ARE COMPETITIVE WITH CONVENTIONAL GENERATION WHEN ARRAY COST IS \$100-200/kW_{pk}, EVEN WITHOUT
 - USE OF CONCENTRATORS
 - PRODUCTIVE UTILIZATION OF THERMAL ENERGY REMOVED IN COOLING ARRAYS
 - RELAXATION OF CURRENT RIGID UTILITY-SYSTEM RELIABILITY STANDARDS
 - INTRODUCTION OF GOVERNMENT INCENTIVES TO ENCOURAGE SOLAR ENERGY USE
 - SUBSTANTIAL CAPACITY DISPLACEMENT IS ACHIEVED
 - ARRAY COST GOALS DEPEND STRONGLY ON FUEL PRICE PROJECTIONS, ARRAY EFFICIENCY
 - USE OF INSOLATION FORECASTING TO GUIDE MANAGEMENT OF ON-SITE STORAGE DOES NOT LEAD TO SIGNIFICANT ADVANTAGE
- USE OF PHOTOVOLTAIC POWER FOR ELECTROLYTIC PRODUCTION OF HYDROGEN IS UNLIKELY TO BE COMPETITIVE WITH ALTERNATE FUELS OR ALTERNATE SOURCES OF HYDROGEN

Chart 45

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