A TECHNIQUE FOR DETERMINING SOLAR INSOLATION DEFICITS*

C.C. Gonzalez**
R.G. Ross***
Jet Propulsion Laboratory
Pasadena, California
91103 USA

ABSTRACT

An analysis technique, involving the use of computer assisted data reduction techniques, has been developed to determine the variation of solar irradiance from long-term averages. The objective of the study was to develop a tool which would enable solar system designers to determine the amount of backup and/or storage capability required to supplement a baseline system sized according to long-term averages. The technique allows the determination of variations for intervals of time up to 60 days. This paper presents results of the analysis of 10 sites in the Continental United States.

1. INTRODUCTION

In support of the U.S. Department of Energy photovoltaics program the Jet Propulsion Laboratory's Low-Cost Solar Array Project is managing and carrying out a number of activities to accelerate the development and large-scale utilization of photovoltaics for various terrestrial applications. One key operational characteristic of photovoltaic arrays, as well as of solar arrays in general, is the dependency of the array output on climatically induced variations in the daily solar irradiance. This variability of the array level is accommodated within the solar system by adding storage, backup power and/or oversizing the array. To allow site and cost optimization of these storage and backup energy sources, it is useful to have an accurate statistical understanding of the degree of array output variation due to weather patterns which can be expected for typical sites in the United States.

Because monthly average values for solar irradiance exist for a vast number of sites, the seasonal variation of average irradiance is well understood and documented (1,2). This study builds upon this base by developing probability statistics defining the expected year-to-year, week-to-week, and day-to-day deviations from these long-term monthly averages.

2. APPROACH

To obtain the desired probability statistics a special methodology was developed to computer analyze 10 years of hourly irradiance data for each of 10 sites in the United States. Total horizontal irradiance as defined on SOLMET data tapes (3) was used as the hourly data source.

Because only the deviation from the long-term average was desired, it was first necessary to determine the long-term smoothed average for each day of the year for each site. This was done by calculating average irradiance values for each month of the year based on the 10 years of data, and then constructing a smooth function through these monthly values. Figure 1 depicts the long-term average irradiance calculated for Miami in comparison with typical published data (2) for the monthly average. It is clear from Figure 1 that each day or period must be compared with the same period each year to separate out the seasonal variation from the year-to-year variation.

Given the long-term averages for the selected sites, the next task is calculating the actual random deviation from these averages during the 10 years of data collection. Because energy storage systems provide a given quantity of energy (irradiance x time), it is necessary to examine the deviation from the average irradiance over various lengths of time. From an energy point-of-view one day with no sun (one no-sun day) is equivalent

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**Member of Technical Staff, Engineering Area, Low-Cost Solar Array Project, Energy Technology Engineering Section.
*** Engineering Manager, Low-Cost Solar Array Project, Energy Technology Engineering Section.

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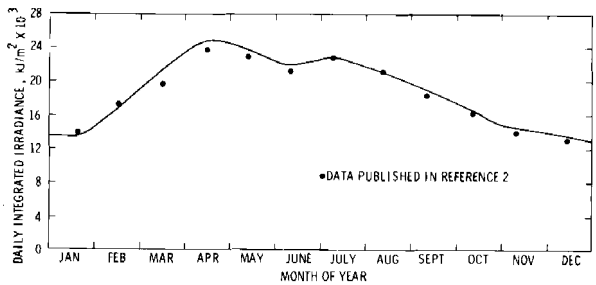

Fig. 1. Long-term average daily solar irradiance on a horizontal surface for a typical site (Miamia, Fla.)

to two days 50% below average or 10 days 10% below average. To account for this time-dependence, deviations from the average irradiant energy were calculated for 16 different time intervals ranging from one day to 60 days. Because irradiance deviation statistics were expected to vary with time of year, the statistics were determined separately for six times of year using 60-day periods centered on the 15th day of February, April, June, August, October and December.

To clarify the calulation procedure, it is useful to consider an example such as the June time period in Miami. The overall objective is to determine the probability of obtaining various levels of solar energy (integrated irradiance over a period of time) during the June time period in Miami as compared to that predicted by the long-term average in Figure 1. The probabilities of obtaining a particular energy level are obtained by examining 10 different Junes, each associated with one of the 10 years of SOLMET tape data.

Next it is necessary to determine the actual solar energy deviation from the long term average for each June. To accomplish this the actual irradiance from the SOLMET tapes was repeatedly integrated for consecutive-day intervals of length equal to 1, 2, 3, 4, 5, 6, 8, 10, 12, 15, 20, 25, 30, 40, 50 and 60 days. Approximately 30 intervals of each interval length were utilized within the 60-day period starting around May 15th and ending around July 15th. Figure 2 illustrates the consecutive-day intervals analyzed. The results of the analysis for each year were displayed as shown in Figure 3, which is an abbreviated form of the actual output matrix. The numbers in each row of this matrix represent the fraction of consecutive-day intervals within the 60-day period which had integrated irradiance levels differing from the average by the percentage shown in the far lefthand column. In the detailed analysis the degree of energy deviation was actually subdivided into 24 levels rather than the eight percentage levels shown. The actual percentage deviation was calculated as:

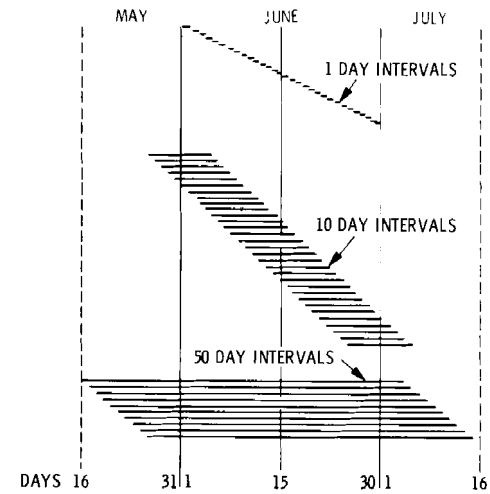

Fig. 2. Illustration of approach used to determine solar irradiance deviations from the long-term average

IRRADIANCE DEVIATION FROM AVERAGE, %	1	2	5	10	20	40	60
POSITIVE 50 - 100							
POSITIVE 20 - 50	0.33	0.23					
POSITIVE 10 - 20	0.13	0.23	0.40	0.43	0.40		
POSITIVE 0 - 10	0.13	0.13	0.30	0.20	0.23	1.00	1.00
NEGATIVE 0 - 10	0.13	0.17	0.10	0.17	0.37		
NEGATIVE 10 - 20	0.067	0.10	0.10	0.20			
NEGATIVE 20 - 50	0.17	0.13	0.10				
NEGATIVE 50 - 100	0.033						

INTERVAL LENGTH, days

Fig. 3. Fraction of consecutive-day intervals around June 1974 during which the integrated irradiance deviated from the long-term average by the percentage shown (Miami, Fla.)

$$\text{Percentage Deviation} = \left(\frac{\int_{d_1}^{d_2} S\,dt - \int_{d_1}^{d_2} \bar{S}\,dt}{\int_{d_1}^{d_2} \bar{S}\,dt} \right) \times 100 \qquad (1)$$

where S = actual hourly irradiance level

$\bar{S}$ = smoothed monthly average irradiance (Figure 1)

d_1, d_2 = start and end date of time interval

The format of Figure 3 allows rapid assessment of the degree of deviation encountered and the maximum deviation encountered as a function of the length of the time interval. For sizing system storage or backup requirements, the most useful information is indeed the maximum deficit expected as a function of the time interval length.

To obtain the probabilities of obtaining a particular maximum deficit any given year, the analysis presented in Figure 3 was repeated for each of the 10 years. The maximum deficits for each interval for each year were then collected in a similar matrix as shown in Figure 4 (again in abbreviated form). In this matrix the numbers in each row represent the number of times out of 10 that the greatest energy deficit from the long-term average was in the percentage range indicated. These entries, when divided by 10, thus represent the probability of obtaining a particular maximum deficit any given year. To aid in assessing the results, marks have also been added indicating the 50% probability, or mean deficit level, and the two standard deviation (2% probability) worst-case deficit level to be expected.

The analysis was completed for each site by generating the data illustrated in abbreviated form in Figure 4 for each of the six 60-day periods of the year. A complete set of the final data will be published in a JPL Low-Cost Solar Array Project document later in 1981.

3. ANALYSIS OF RESULTS

The matrices symbolized by Figure 4 for each site contain a wealth of information. One important use of the data is the sizing of system storage and the oversizing of the array collector area to satisfy the predicted energy deficits. One means of characterizing storage is in terms of "no-sun days." With this nomenclature, a storage of two no-sun days has an energy storage capacity equal to twice the energy delivered by the collector array in one day under the long-term average conditions as depicted in Figure 1. This storage system would be capable of delivering enough energy to cover a 100% deficit for two days, or a 50% deficit for four consecutive days, etc.

DEFICIT SIZE %	NUMBER OF YEARS OUT OF TEN						
0 - 10	0	0	0	1	5	3 +	2 +
10 - 20	0	0	2	3	2	2 ◎	2 ◎
20 - 50	3	8	8 ◎	6 ◎	3 ◎	0	0
50 - 100	◎ 7	2 ◎	0	0	0	0	0
	1	2	5	10	20	40	60

INTERVAL LENGTH, days

+ IN SOME YEARS WORST CASE ABOVE AVERAGE
50% PROBABILITY OF OCCURRENCE
◎ 2% PROBABILITY OF OCCURRENCE

Fig. 4. Number of years out of ten during which the worst-case energy deficit fell in the percentage category shown for June in Miami, Fla.

Figure 5 presents in graphic form the mean and 2 standard deviation worst-case deficit data from Figure 4 in terms of the fractional deficit for a given interval length. For example, a 0.1 deficit indicates that the energy deficit is 10% of the long-term average energy for that interval. Overlayed on these curves are constant "no-sun day" curves which are indicators of the degree of deficit that can be accommodated by various levels of storage.

The deficit curves shown in Figure 5 can be broken down into two components: the asymptotic value to which the curves tend for long intervals of time, and the deficit measured for short intervals of time. The asymptotic value is an indication of the long-interval deficit. Note that the largest no-sun-day deficits tend to be associated with longer intervals (from 30 to 60 days) with worst-case deficits on the order of 15% below the long term average.

An important observation from Figure 5 is that it may be more cost-effective to accommodate the long-interval deficits by increasing the collector array size as opposed to adding energy storage capacity, which is the most cost-effective way to handle short-interval deficits. For example, a 10% deficit over 60 days can be accommodated by a 10% increase in collector area or by a storage capacity of 0.10 x 60 = 6 no-sun days. The data illustrated in Figure 5 are valuable in allowing storage versus collector size cost trade-offs of this type to be conducted.

Figure 6 summarizes the worst-case deficits (2% probability of occurrence) for six bimonthly intervals for 10 sites. The values presented in the histogram represent the short-term no-sun-day deficits which remain after the collector array has been oversized by 15% to handle the long-term deficits. Note also from Figure 6 that the maximum deficit in no-sun days varies from site to site. This implies that the storage required to cover random weather variations is a varying percentage of the collector energy production for different sites, ranging from one to nine no-sun days. An additional no-sun day would also be required for systems whose primary loads are at night and must store energy for use the same calendar day. Of course other factors affecting the sizing of storage also exist, including a margin for larger than usual loads, seasonal load leveling, and controlling the depth of discharge to prolong battery life and reliability.

4. CONCLUSIONS

A novel technique has been developed for determining the probability statistics associated with climatic variations in average solar irradiance. Results obtained

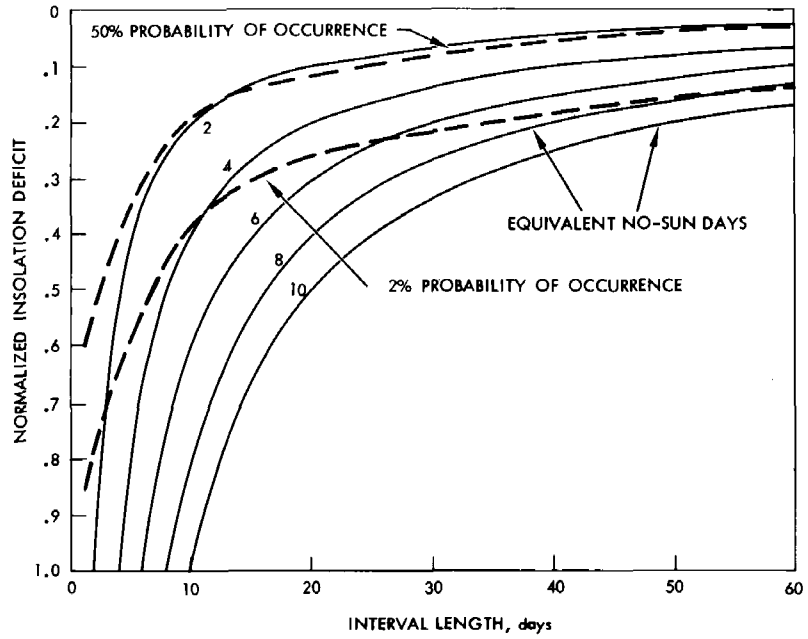

Fig. 5. Solar irradiance deficit for June in Miami, Fla. as a function of interval length

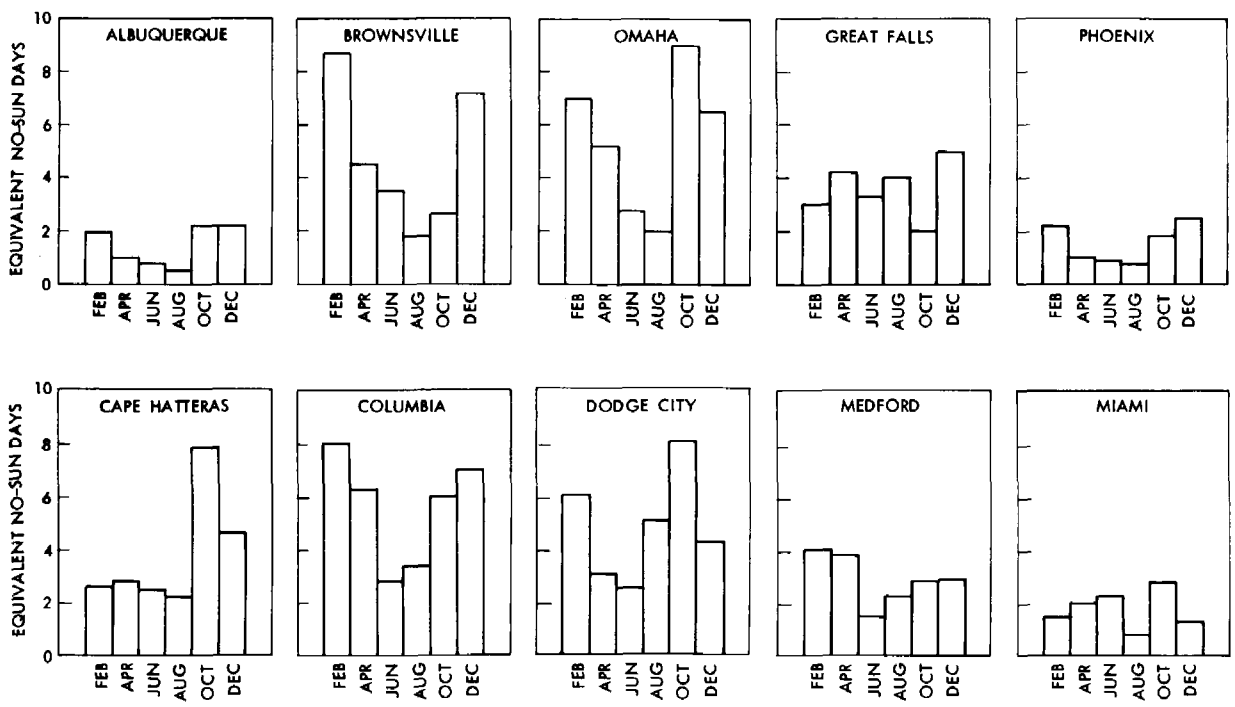

Fig. 6. Two percent probability worst-case deficits assuming a 15% oversized array

by using this technique have been presented for 10 sites in the United States for different times of the year. It has been shown that the cost-effective accommodation of solar irradiance deficits probably includes both increasing the collector area by approximately 15% to cover long term year-to-year variations from the average, and adding energy storage or backup to cover short term "local storm"-caused deficits. Site-to-site dependency exists, causing a range of required short term storage capacities of one to nine no-sun days to accommodate the weather-caused deficits for this broad variety of sites.

5. REFERENCES

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