A Technique for Determining Solar Irradiance Deficits

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Key Words—**Photovoltaics, Solar irradiance, Solar energy deficit, Array, Collector and storage sizing.**

Reader Aids—
Purpose: Advance state of the art
Special math needed for explanations: None
Special math needed for results: Statistics
Results useful to: Photovoltaic array designers

Summary and Conclusions—**A novel analytic 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 that would enable solar system designers to assess and improve overall system reliability by determining 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 13 sites in the continental USA.**

Cost-effective accommodation of solar irradiance deficits includes both increasing the collector area by about 15% to cover long-term year-to-year variations from the average, and adding energy storage or backup to cover short-term deficits such as those caused by local storms. Site-to-site dependency exists, causing a range of required short-term storage capacities of 1 to 7 no-sun days to accommodate the weather-caused deficits for this broad variety of sites.

1. INTRODUCTION

The reliability of terrestrial photovoltaic arrays is fundamentally important in determining system life-cycle cost. See companion paper in this issue, and [1, 2]. However, such studies usually emphasize hardware reliability rather than the reliability of solar irradiance on which array output depends. Climatically induced variations in the daily solar irradiance, which are difficult to estimate accurately, can reduce array output below that required to meet a given load profile. The baseline array is usually sized from long-term average irradiance levels [3, 4]. The variability of the array level is accommodated within the system by adding storage, stand-alone backup power sources, 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 that can be expected for typical sites in the United States. Use of utility backup would introduce additional complexities, e.g., the interaction of the photovoltaic system and utility grid.

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 [3, 4]. This study builds upon this base by developing probability statistics defining the anticipated year-to-year, week-to-week, and day-to-day deviations from these long-term monthly averages.

2. APPROACH

To obtain the desired statistics, a special method was developed to computer-analyze 10 years of hourly irradiance data for each of 13 sites in the USA. Total horizontal irrandiance as defined on SOLMET (solar radiation -surface meteorological observations) data tapes [5] 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 [4] 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 the seasonal variation from the year-to-year variation.

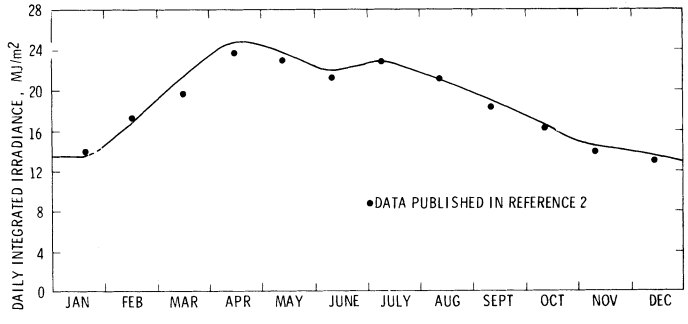

Fig. 1. Long-term Average Daily Solar Irradiance on a Horizontal Surface for a Typical Site (Miami, Florida).

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 × time), it is necessary to examine the deviation from the average irradiance over various lengths of time. From an energy point of view, 1 day with no sun (one no-sun day) is equivalent to 2 days of 50%-below-average irradiance or 10 days at 10% below average. To account for this time-dependence, deviations from the

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average irradiant energy were calculated for 16 different time intervals ranging from 1 day to 60 days. Because irradiance-deviation statistics were anticipated to vary with time of year, the statistics were determined separately for six times of year using 60-day periods centered on the 15-th day of February, April, June, August, October, and December.

To clarify the calculation procedure, it is useful to consider an example, such as June 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 June in Miami, compared with that predicted by the long-term average in figure 1. The probability densities of obtaining a specific energy level are obtained by examining 10 different Junes, each associated with one of the 10 years of SOLMET tape data.

Next is 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 integrated repeatedly for consecutive-day interval lengths ranging from 1 to 60 days. Up to 60 consecutive-day intervals of each interval length were used within the 60-day period starting about May 15 and ending about July 15. Figure 2 illustrates the concept used in analyzing the consecutive-day intervals. 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 that had integrated irradiance levels differing from the average by the percentage shown in the far left-hand column. In the detailed analysis, the degree of energy deviation was subdivided into 24 levels rather than the eight percentage levels shown. The actual relative deviation was calculated as:

$$\text{Relative deviation} = \frac{\int_{d_1}^{d_2} S\,dt - \int_{d_1}^{d_2} \bar{S}\,dt}{\int_{d_1}^{d_2} \bar{S}\,dt} \qquad (1)$$

S actual hourly irradiance level
$\bar{S}$ smoothed monthly average irradiance (figure 1)
d_1, d_2 start date 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 the maximum deficit anticipated as a function of the interval length.

To obtain the probabilities of obtaining a specific maximum deficit for 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 (shown in figure 4 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, represent the probability of obtaining a specific maximum deficit in any given year. To aid in assessing the results, marks have also been added indicating the 50% probability deficit level, and the 10-year extreme limit (10% probability) worst-case deficit levels to be expected.

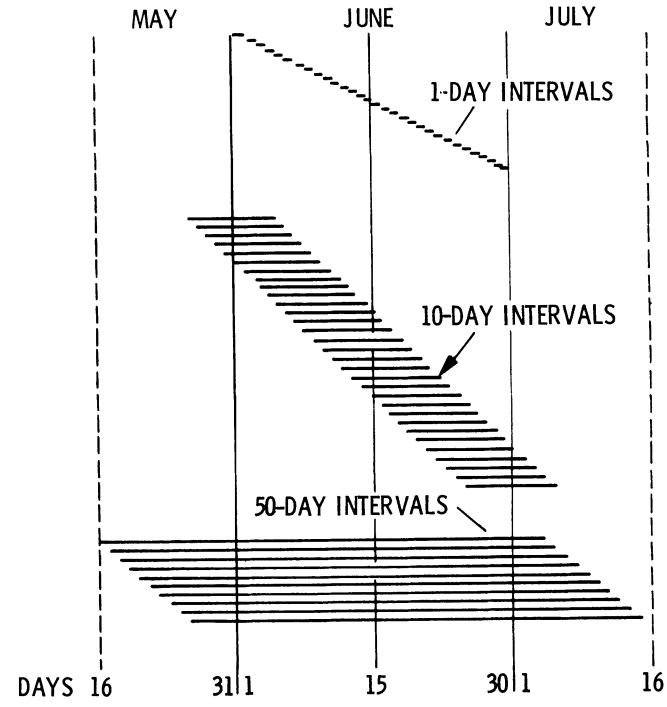

Fig. 2. Illustration of Approach Used to Determine Solar Irradiance Deviations from the Long-term Average.

IRRADIANCE DEVIATION FROM AVERAGE, %	1	2	5	10	20	40	60
50 - 100 (POSITIVE)							
20 - 50 (POSITIVE)							
10 - 20 (POSITIVE)							
0 - 10 (POSITIVE)	0.70	0.67	0.56	0.86	0.95	1.00	1.00
0 - 10 (NEGATIVE)	0.16	0.24	0.44	0.14	0.05		
10 - 20 (NEGATIVE)	0.12	0.07					
20 - 50 (NEGATIVE)	0.02	0.02					
50 - 100 (NEGATIVE)							

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, Florida).

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 is published in [6].

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 compensate for the predicted energy deficits. One means of characterizing storage is in terms of "no-sun days." With this nomenclature, a storage capacity of 2 no-sun days is an energy storage capacity equal to twice the energy delivered by the collector array in 1 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 2 days, or a 50% deficit for 4 consecutive days, etc.

DEFICIT SIZE %	NUMBER OF YEARS OUT OF TEN						
0 - 10	0	0	5	8*	8 *⊛+	5 *⊛+	3 *⊛+
10 - 20	0	2	4*	2⊛	0	0	0
20 - 50	7*	7*	1⊛	0	0	0	0
50 - 100	3⊛	1⊛	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
⊛ 10% PROBABILITY OF OCCURRENCE

Fig. 4. Number of Years Out of 10 during which the Worst-Case Energy Deficit Fell in the Percentage Category Shown for June in Miami, Florida.

Figure 5 presents the mean and 10-year extreme limit deficit data from figure 4 as 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. Overlaid on these curves are constant "no-sun-day" curves that indicate the degree of deficit that can be accommodated by various levels of storage.

The deficit curves shown in figure 5 can be reduced to 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; the largest no-sun-day deficits tend to be associated with longer intervals (from 30 to 60 days) with worst-case deficits 15% below the long-term average.

An important observation from figure 5 is that it might be more cost-effective to accommodate the long-interval deficits by increasing the collector array size instead of adding energy storage capacity, which is the most cost-

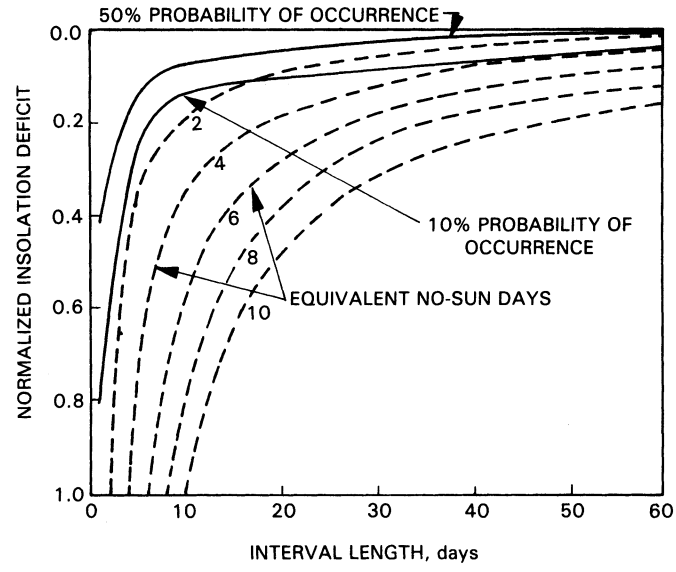

Fig. 5. Solar Irradiance Deficit for June in Miami, Florida as a Function of Interval Length.

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 $0.10 \times 60 = 6$ no-sun days. The data illustrated in figure 5 are valuable in allowing storage vs collector-size cost tradeoffs of this type to be made.

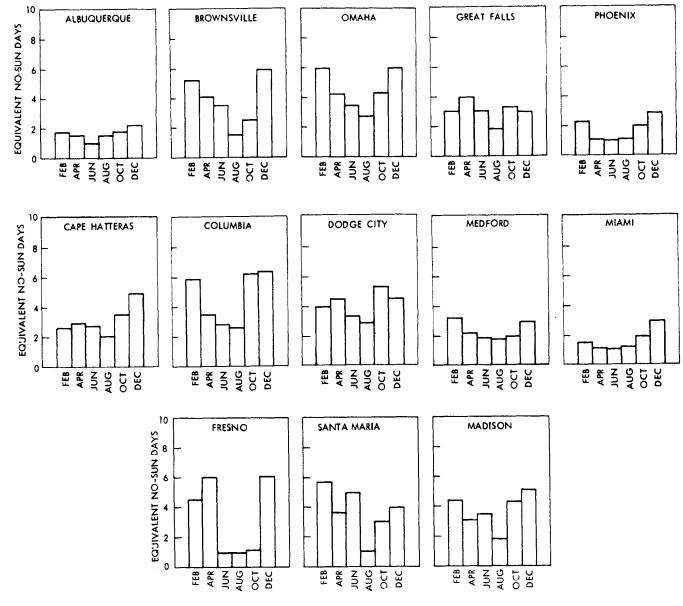

Fig. 6. Ten-Percent Probability Worst-Case Deficits Assuming a 15%-Oversized Array.

Figure 6 summarizes the worst-case deficits (10% probability of occurrence) for six bimonthly intervals for 13 sites. The values presented in the histogram represent the short-term no-sun-day deficits that remain after the collector array has been oversized by 15% to handle the long-term deficits. From figure 6, 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 1 to 7 no-sun days. An additional no-sun day of storage capacity would also be required for systems whose primary loads occur at night and that must store energy for use on the same calendar day. 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.

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REFERENCES

[1] C. Gonzalez, R. Weaver, "Circuit Design Considerations for Photovoltaic Modules and Systems," *Proc. 14-th IEEE Photovoltaic Specialists Conference*, San Diego, California, 1980 January 7-10, pp 528-535.

[2] R.G. Ross, Jr., "Flat-Plate Photovoltaic Array Design Optimization," *ibid*, pp 1126-1132.

[3] *Handbook of Solar Energy Data for South-Facing Surfaces in the United States*, JPL Publication No. 79-103, Volumes I, II, III (DOE/JPL-1012-25), January 15 1980.

[4] *Climates of the States*, Volumes I and II, National Oceanic and Atmospheric Administration, US Department of Commerce, 1974.

[5] National Climatic Center, *SOLMET: Volume I--User's Manual.* National Oceanic and Atmospheric Administration, North Carolina 1977.

[6] "Analysis of long-term solar irradiance deficits for sites in the United States," JPL Publication 5101-208 (in press, C. 1982).

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