PERFORMANCE MEASUREMENT REFERENCE CONDITIONS FOR TERRESTRIAL PHOTOVOLTAICS*

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ABSTRACT

One important aspect of measuring terrestrial photovoltaic array electrical performance is the choice of a reference solar spectrum. Sensitivity to this choice is caused by the narrow spectral response of photovoltaic materials and the associated dependency of certain annual energy output calculational procedures. The accuracy of energy output calculations based on commonly used reference spectra is examined for a variety of array types and site locations in the U. S. using tapes of hourly solar irradiance and temperature measurements in conjunction with solar spectrum models. Conclusions are drawn relative to the accuracy associated with the commonly used air mass 1.5 reference spectrum, and alternative reference spectra with improved accuracy are illustrated.

1. INTRODUCTION

The Jet Propulsion Laboratory's (JPL) Low-cost Solar Array (LSA) Project has primary responsibility within the Department of Energy's national photovoltaics program for managing the development of low-cost flat-plate photovoltaic solar arrays. The development of array performance criteria and measurement methods is an active part of the LSA effort and directly supports the national photovoltaic standards activity led by the Solar Energy Research Institute (SERI) and the various consensus standards organizations, such as ASTM and IEEE. The historical need for performance reference conditions is based on the strong dependency between photovoltaic electrical output and two key measurement variables: the level and spectral composition of the incident irradiance, and the junction temperature of the photovoltaic device.

1.1 Reference Irradiance Conditions

The spectral composition of a given irradiance is important to photovoltaic measurements because the conversion efficiency of photovoltaic materials is strongly dependent on the wavelength of the irradiance. Figure 1 illustrates the relative spectral response of a silicon cell together with two common solar irradiance spectrums. Other photovoltaic materials such as cadmium sulfide and gallium arsenide have similar responses, but they peak in slightly different wavelength regions.

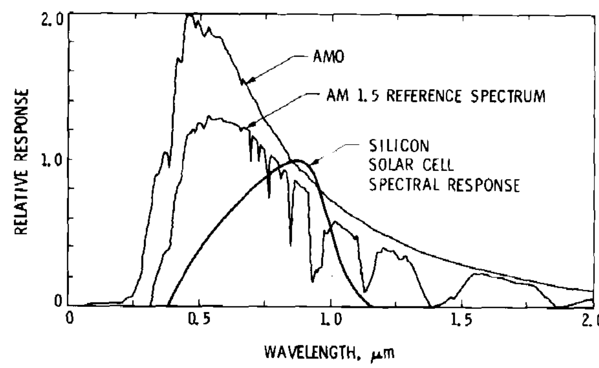

Fig. 1 - Typical solar cell spectral response versus two solar irradiance spectra

Although a photovoltaic spectral response curve such as that shown in Figure 1 is sometimes used to accurately quantify cell electrical performance, the format of the presentation does not provide a ready estimation of typical terrestrial sunlight performance which is required when comparing the performance of devices with dissimilar spectral responses. To meet this need an alternative approach is widely used based on reporting photovoltaic output for a particular terrestrial sunlight reference level and spectrum. With this approach the

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spectral response of the device is replaced by a single performance quotation of electrical output for the reference irradiance conditions.*

At present the most widely used reference condition for terrestrial applications is a total irradiance level of 100 mW cm^{-2} with the Air Mass 1.5 spectrum shown in Figure 1 as documented in Reference 1.

1.2 Reference Temperature Conditions

The second major parameter affecting photovoltaic electrical output is the junction temperature of the photovoltaic device. As shown in Figure 2, temperature primarily affects output voltage, whereas irradiance and spectrum primarily affect output current.

Although the selection of the cell reference temperature is as important as the choice of the reference spectrum, it can be separated from the selection of the reference spectrum and has been treated in detail in a companion paper by these same authors (2).

2. STUDY OBJECTIVE AND APPROACH

Considerable interest and activity presently exists within the international photovoltaic community relative to developing consensus standards for photovoltaic solar irradiance reference conditions. The present study was initiated in support of this activity in an attempt to identify quantitative rationale to aid either in choosing among or building upon the present alternatives.

For many, the primary use of reference conditions is to provide a common baseline

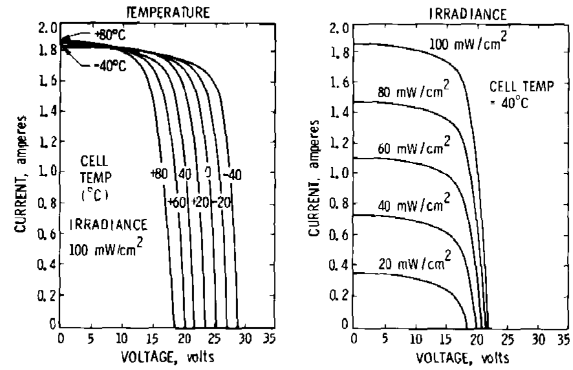

Fig. 2 - Typical silicon photovoltaic module temperature/irradiance-level dependence

for performance comparison of various photovoltaic devices. The type of comparison being made influences the type of reference conditions preferred. One generic class of uses is associated with comparing the lot-to-lot or unit-to-unit performance of a single device type as typified by product quality control activities.

A second generic class of uses is associated with comparing the performance of competing products for either a specific application at a known site location, or a generic class of applications at a variety of sites. For this class of uses the optimum reference conditions are those which provide, or easily lead to, an accurate measure of field application performance.

Associated with this latter set of uses is a generally overlooked and very important indirect use of reference conditions in conjunction with photovoltaic system performance simulation and prediction. When photovoltaic reference-condition performance is imbedded in energy performance calculations for photovoltaic arrays and systems the choice of reference conditions directly controls the accuracy of these approximations.

The remainder of this paper examines the relationship between the choice of reference irradiance conditions and the accuracy of photovoltaic energy calculations.

3. IMPLICATION OF ENERGY CALCULATIONS ON REFERENCE SPECTRUM

As a first step in understanding the implications of energy calculations on the reference spectrum it is useful to examine the mathematical relationship which describes electrical energy production in terms of fundamental photovoltaic and environmental parameters. In complete form the annual energy production of an array is described by the following equation:

* Implementation of this approach can lead to certain practical problems caused by the fact that performance measurements are generally made under simulated sunlight or outdoor sunlight conditions which differ in level and spectral content from the reference conditions. This requires that the measured performance be extrapolated to the reference conditions for reporting purposes. Although the extrapolation can be accomplished analytically if the spectral characteristics of the test irradiance and photovoltaic device are known, the more common practice is to utilize a "reference solar cell" whose reference-condition output is accurately known and whose spectral response matches that of the test device. Accurate determination of the reference-condition performance of the test device is thus accomplished by comparing its measured output to that of the reference cell under the same test irradiance.

$$\text{Annual Energy}/m^2 = \int_{yr} \int_{\lambda} S_\lambda(t)\, \eta_\lambda(T)\, d\lambda\, dt \quad (1)$$

Where: S_λ = Spectral Irradiance at Time (t), $W\ m^{-2}\ um^{-1}$

η_λ = Array Spectral Electrical Efficiency

T = Cell Temperature at Time (t), ^oC

Unfortunately, the lack of hourly spectral irradiance data for potential photovoltaic geographic sites effectively prevents the use of equation 1 for energy calculations. Therefore, the following simplification is made to allow application of hourly total irradiance and ambient temperature data:

$$\int_{yr} \int_{\lambda} S_\lambda(t)\, \eta_\lambda(T)\, d\lambda\, dt \approx \int_{yr} S(t)\, \eta(T)\, dt \quad (2)$$

Where: S = Total (pyranometer) Irradiance at Time (t), $W\ m^{-2}$

η = Array Efficiency for Reference Spectrum

T = Cell Temperature at Time (t), ^oC

The above approximation serves as a primary constraint on the selection of the reference spectrum used to define array efficiency. For accurate energy calculations it is necessary that the reference spectrum be chosen to give a good approximation between the two integrals of equation 2.

To provide a quantitative assessment of the currently used reference spectra the integrals representing the two sides of equation 2 were computed for a variety of site locations around the United States using measured hourly data for solar irradiance and ambient temperature together with measured parameter dependencies for a typical silicon photovoltaic array (3). Cell temperature of a typical array was computed in terms of ambient air temperature (^oC) and incident solar irradiance (S, mW cm^{-2}) using the following relationship based on previous JPL field measurements (4):

$$T_{cell} = T_{air} + 0.3\ S,\ ^oC \quad (3)$$

Because measured hourly spectral irradiance data were unavailable, the data necessary for the integration were manufactured using a combined analytical and empirical approach. In this approach the direct normal and diffuse sky spectral irradiance were computed separately using analytical and experimental derived models and then combined prior to performing the convolution with the cell spectral response.

The direct normal spectral irradiance was computed using a revision of a computer program of the late Dr. M. P. Thekaekara developed by NASA Lewis Research Center (1). The program begins with the NASA standard Air Mass Zero solar spectral irradiance and attenuates it for the various scattering and absorbing processes (5). The NASA-Lewis revisions include provision for forward scattering and elimination of most of the water vapor absorption in the Thekaekara model between the wavelengths of .835 and .925 micrometers. After computing the direct normal spectral distribution using hourly data for air mass and monthly data for water vapor, the total direct normal irradiance level was scaled to equal the hourly value from the SOLMET weather tape for the site of interest.

Because of the lack of easily implemented analytical models for the diffuse sky spectral irradiance a measurement program was carried out as part of this JPL study to empirically characterize the diffuse sky spectral irradiance by making measurements at Pasadena, California, during September and October 1979 and during January 1980. Typical representative spectra, one characteristic of clear weather conditions and one characteristic of cloudy conditions, are shown in Figure 3. These typical diffuse spectra were used for the diffuse sky spectral irradiance distributions for all site locations examined in the hour-by-hour energy calculation analysis. A check on the sensitivity of the results for a given site was made by performing the spectral integration using the clear day diffuse model and the cloudy day model and comparing results. As with the direct normal, the hourly total irradiance level of the diffuse sky irradiance was scaled to equal that computed from the SOLMET tape.

As a final step annual energy was computed for both a two-axis-tracking concentrator array (direct normal only) and a fixed-latitude-tilt flat-plate array using the above data together with equation 2 . The calculation of incident irradiance on a

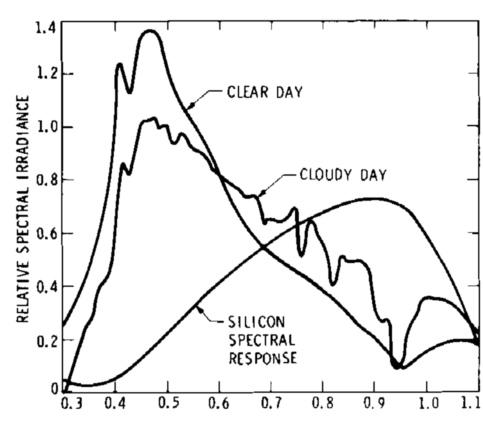

Fig. 3 - Typical diffuse sky spectral distributions normalized for equal total irradiance

tilted array was based on an algorithm developed originally by Liu and Jordan and modified by Klucher (6). Two sites, Albuquerque, New Mexico, and Miami, Florida, were chosen as the principal sites for the study because they represent climatological extremes. Albuquerque is noted for its high direct to diffuse ratio, whereas Miami has a very large diffuse contribution. Table 1 presents the results of the integration comparison.

As the results indicate, the two integrals in equation 2 are in good agreement for concentrator arrays. This implies that the Air Mass 1.5 reference spectrum used for the analysis is a good representation of the average direct normal spectral distribution at these sites. On the other hand, agreement for the flat-plate array is not as good, particularly for Miami. The major cause of the inaccuracy is traceable to the much bluer average solar irradiance for a flat-plate array due to the contribution of the blue diffuse sky irradiance, and due to the attenuation of the direct normal by the cosine of the angle of incidence.

The sensitivity of these results to the assumed diffuse spectral distribution was obtained by re-computing the integrals using each of the distributions shown in Figure 3. The results for Albuquerque differed by only 2.5 percent, indicating relative insensitivity to the diffuse model. The results presented in Table 1 for Albuquerque are those for the clear day diffuse spectrum which was felt to be more representative for this site. The results for Miami differed by 6.5 percent, reflecting the greater contribution of the diffuse (nearly 40%) to the total flat-plate irradiance. Because of the cloudy conditions associated with Miami the results in Table 1 for this site are a median of the results from the clear and cloudy day diffuse spectra.

As a next step in understanding the spectral distribution seen by a flat-plate array, the annual incident irradiant energy was computed as a function of wavelength for the two sites. The results, shown in Figure 4, can also be interpreted as the weighted average spectral irradiance where the weight is the hourly total irradiance level on the array surface. As seen, the Air Mass 1.5 reference spectrum normalized to the same total irradiance has excessive energy in the red region of the spectrum and is deficient at the blue end.

Table 1 - Annual Energy Calculation Summary

PARAMETER	UNITS	CONCENTRATOR ALBUQUERQUE	CONCENTRATOR MIAMI	FLAT PLATE ALBUQUERQUE	FLAT PLATE MIAMI
TOTAL IRRADIANT ENERGY $E_s = \int_{yr} S\,dt$	$kWh/m^2/yr$	2573	1394	2244	1916
TOTAL ARRAY OUTPUT $E = \int_{yr} S(t)\eta(T)\,dt$	$kWh/m^2/yr$	237.3	124.5	206.5	170.2
TOTAL ARRAY OUTPUT $E_\lambda = \int_{yr}\int_{\lambda} S_\lambda(t)\eta_\lambda(T)\,d\lambda\,dt$	$kWh/m^2/yr$	237.7	127.1	194.4	157.5
ENERGY OUTPUT RATIO E/E_λ	-	0.9983	0.9795	1.062	1.081

$\eta(T) = \eta_\lambda(T)$ WITH AM 1.5 REFERENCE SPECTRUM

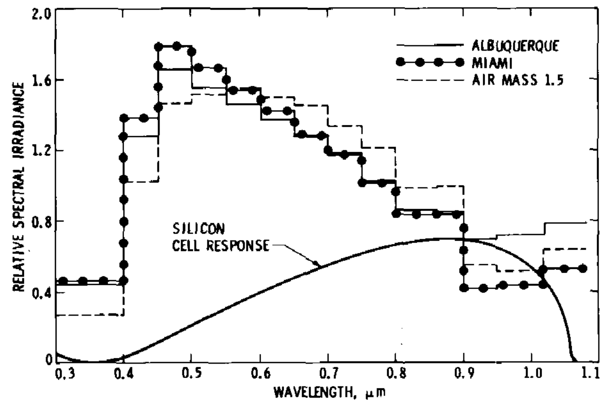

Fig. 4 - Comparison of annual irradiant energy spectral distributions with AM 1.5 reference spectrum normalized for equal total irradiance

As a further experiment the irradiant energy spectra shown in Figure 4 were used as the reference spectra for their respective sites and the annual energy integrations repeated. As shown in the first column of Table 2, these spectra vastly improve the accuracy of the energy calculation with an error of less than two percent. This small error is likely caused by the influence of solar cell temperature on efficiency, which is not factored into the irradiant energy spectral distribution. Because cell efficiency decreases with increased temperature, cell temperature weights more heavily those hourly irradiance spectra associated with low irradiance levels and low air temperatures.

In an attempt to further define the most appropriate flat-plate reference spectrum a number of conventional terrestrial spectra were evaluated in the same way as above. The results of the annual energy integration, shown in Table 2, indicate that a reference spectrum slightly bluer than Air Mass 1 provides the best match for both integrals of equation 2. The Air Mass 2 spectrum leads to an over prediction of annual energy because it contains more energy than the average annual spectrum in the region of greatest cell response. The Air Mass 0 spectrum contains too little energy in this region.

In making a final spectrum choice it must be remembered that the response curve used here is for a typical silicon cell. Solar cells

Table 2 - Energy Output Ratio Summary

SITE LOCATION (DIFFUSE MODEL)	$E/E_\lambda = \int_{yr} S(t)\,\eta(T)\,dt \Big/ \int_{yr}\int_{\lambda} S_\lambda(t)\,\eta_\lambda(T)\,d\lambda\,dt$				
	REFERENCE SPECTRUM				
	ANNUAL ENERGY	AM 0	AM 1.0	AM 1.5	AM 2.0
ALBUQUERQUE	0.98	0.87	1.01	1.06	1.11
MIAMI (MEDIAN)	0.99	0.89	1.03	1.08	1.13
MIAMI (CLEAR)	0.99	0.92	1.07	1.12	1.17
MIAMI (CLOUDY)	0.99	0.86	1.00	1.05	1.10

made of other materials have response curves which peak in slightly different regions. To accurately satisfy the demands of a variety of cell spectral responses it is necessary that the reference spectrum closely match the mean annual irradiant energy spectral distribution for all important wavelengths. This point is illustrated in Figure 5 where the Air Mass 0, 1, 1.5, and 2 spectra are compared with an annual irradiant energy spectral distribution representing a median for Albuquerque and Miami. The silicon cell response curve is also shown. Because none of the conventional spectra match the accuracy obtainable using the annual incident energy spectral distribution, a mean annual energy distribution for a variety of sites could serve as a useful reference spectrum for flat-plate photovoltaic arrays.

4. CONCLUSIONS AND RECOMMENDATIONS

In addition to providing a repeatable reference for performance comparisons, it has been shown that the choice of reference spectrum directly controls the accuracy of array energy output prediction calculations. Examination of the commonly used air mass 1.5 reference solar irradiance

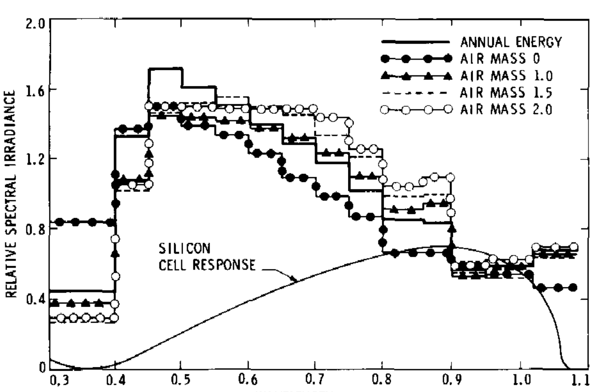

Fig. 5 - Comparison of terrestrial spectra with AM 1.5 reference spectrum normalized for equal total irradiance

spectrum indicates that it provides excellent accuracy for energy prediction for concentrator arrays, but performs less well for flat-plate arrays. The conventional spectrum which provides the least error for flat-plate arrays is similar to, but slightly bluer than an air-mass-one solar spectrum distribution.

A concept worthy of further consideration is the selection of a mean annual irradiant energy spectral distribution derived from an analysis of a variety of site locations. Such an approach offers the potential of improved accuracy in photovoltaic device comparisons and annual energy predictions. To take full advantage of this approach certain improvements should be incorporated into the analysis performed in this study. Particular points include the experimental verification of the direct normal spectral irradiance model and further examination of the spectral characteristics of the diffuse sky. The addition of a diffuse model for a clear, unpolluted sky is a high priority for modeling clear air rural and remote areas.

5. REFERENCES

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