TERRESTRIAL PHOTOVOLTAIC PERFORMANCE REFERENCE CONDITIONS*

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Summary
A comprehensive study has examined the rationale behind the selection of key photovoltaic performance reference (reporting) conditions including the standard Air Mass 1.5 solar spectrum and reference irradiance and cell temperature levels. In addition to providing a repeatable reference for performance comparisons, it is shown that the choice of reference conditions directly controls the accuracy of array energy output prediction calculations. Conclusions are drawn relative to the accuracy associated with present reference conditions, and recommendations are made concerning alternative reference conditions with improved accuracy.

1. INTRODUCTION

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. Although the primary use of reference conditions is to provide a common baseline for performance comparison of various photovoltaic devices, a generally overlooked and very important indirect use of reference conditions is 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 there are a number of implicit approximations which are made. The choice of reference conditions directly controls the accuracy of these approximations. This paper examines the relationship between choice of reference conditions and the ease and accuracy of photovoltaic energy calculations.

2. IMPLICATION OF ENERGY CALCULATIONS ON REFERENCE SPECTRUM

As a first step in understanding the implications of energy calculations on reference spectrum it is useful to examine the mathematical relationship which describes the annual energy production of an array.

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

Where: S_{λ} = Spectral Irradiance at Time (t), W m^{-2} μm^{-1}

η_{λ} = Array Spectral Electrical Efficiency

T = Cell Temperature at Time (t), ^{o}C

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Unfortunately, the total 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, expanding the possibility of application, but still limiting the number of sites to those with hourly irradiance and ambient temperature data available:

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

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

η = Array Efficiency for Reference Spectrum

T = Cell Temperature at Time (t), ^{o}C

The above approximation serves as a primary constraint on 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[1]. 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 (nearly 40%) diffuse contribution. Because measured hourly spectral irradiance data were unavailable, the direct normal and diffuse sky spectral irradiance necessary for integration 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 together with 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. These typical diffuse spectra were used for the diffuse sky spectral irradiance distributions in the hour-by-hour energy calculation analysis. As with the direct normal, the hourly total irradiance level of the diffuse sky irradiance was scaled to equal that from the SOLMET weather data tape.

As an additional 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 1, 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.

As a final step to define the most appropriate flat-plate reference spectrum the irradiant energy spectrum shown in Fig. 1 and a number of conventional terrestrial spectra were used as the reference spectra and the annual energy integrations in equation (2) were computed. From the results in Table 1 it can be seen that the spectrum leading to the lowest error is

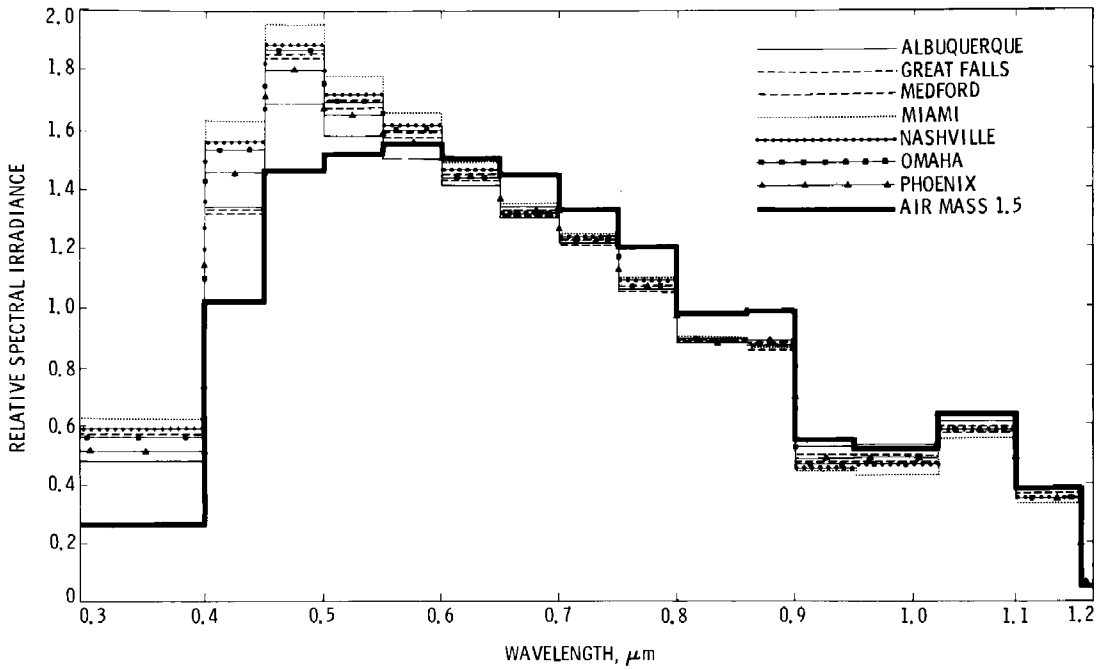

Fig. 1 - Comparison of annual irradiant energy spectral distributions with AM 1.5 reference spectrum normalized for equal total irradiance.

similar to, but slightly bluer than, the air mass 1.5 spectrum. However, 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.

3. IMPLICATION OF ENERGY CALCULATIONS ON REFERENCE TEMPERATURE

Because of the absence of hourly weather data at most sites, additional approximations beyond that of equation (2) are generally required in the computation of annual energy performance. Examination of the implications of this further approximation provides additional insight into the selection of photovoltaic reference conditions.

The general approach to dealing with the lack of hourly irradiance and ambient temperature data is to compute energy production as a product of a nominal photovoltaic efficiency and the total integrated solar irradiant energy at the site of interest. This approximation places further restrictions on the definition of array reference conditions by requiring that the array efficiency be referenced at the particular set of solar irradiance level and cell temperature conditions which maximize the accuracy of the

Table 1 - Annual Energy Calculation Summary

SITE LOCATION	$E/E_\lambda = \int_{yr} S(t)\,\eta(T)\,dt \Big/ \int_{yr}\int_\lambda S_\lambda(t)\,\eta_\lambda(T)\,d\lambda\,dt$				
	REFERENCE SPECTRUM				
	ANNUAL ENERGY	AM 0	AM 1.0	AM 1.5	AM 2.0
ALBUQUERQUE	0.99	0.85	0.98	1.03	1.08
MIAMI	1.00	0.84	0.97	1.02	1.07

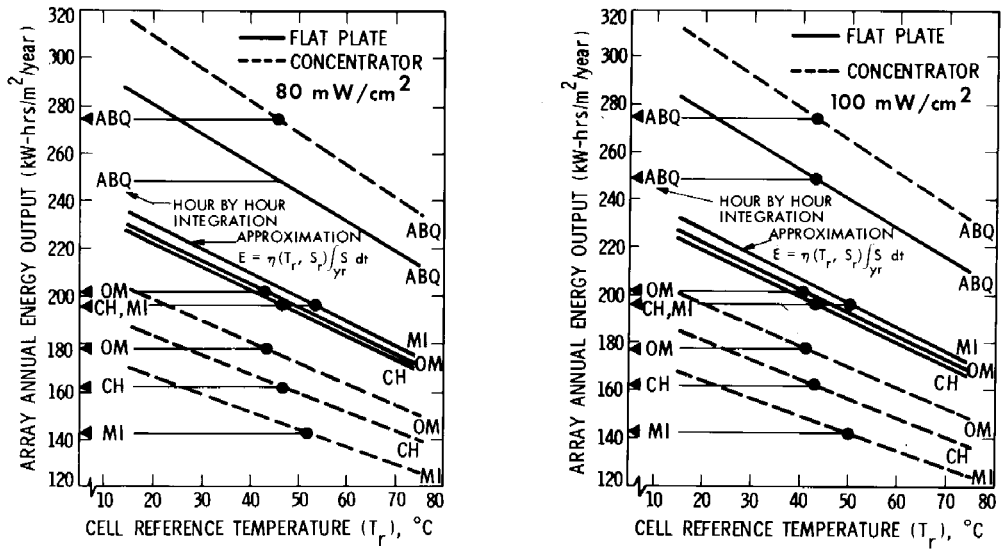

Fig. 2 - Annual energy output versus cell reference temperature (T_r) for a reference irradiance level (S_r) of 80 mW/cm^2 and 100 mW/cm^2.

following mathematical relationship:

$$\int_{yr} S(t)\eta(T)\,dt \approx \eta(T_r, S_r)\int_{yr} S\,dt \qquad (3)$$

Where: T_r = Reference Cell Temperature, °C

S_r = Reference Irradiance Level, mW/cm^2

To provide an assessment of various solar irradiance and cell temperature levels, the computer analysis of equation(2)was extended to include calculation of the right hand side of equation (3) for a variety of solar array types and site locations in the U.S. Figure 2 presents the results of this analysis for selected reference irradiance levels of 80 and 100 mW/cm^2, and for cell reference temperatures from 15 to 75°C. For each site location and array type the cell reference temperature which makes the two sides of equation(3)equal is indicated by the dot and line pointing to the annual energy output computed using the hourly irradiance and temperature data.

For the typical array thermal characteristics used in this study a reference temperature around 45°C appears to provide the best approximation of annual energy output, depending only slightly on the site location and reference irradiance level selected. Unfortunately this optimum reference temperature is only useable for a typical photovoltaic array and is inappropriate for designs with significantly different operating temperatures.

In an attempt to broaden the applicability of reference temperature conditions it is useful to next examine the concept of a reference environmental condition (irradiance level, ambient air temperature, and wind velocity). Use of a reference environmental condition offers the potential of accomodating photovoltaic arrays with diverse thermal designs by avoiding the concept of a fixed cell reference temperature. Instead a unique design-specific cell reference temperature is associated with each array thermal design and equals the cell operating temperature under the reference environmental condition. This design-specific cell reference temperature is referred to as the array's Nominal Operating Cell Temperature (NOCT). Standard tests for determining an array's NOCT are developed in Ref. 2.

To quantitatively assess the alternative fixed reference environmental conditions the integrals in equation (3) were recomputed as necessary using

Table 2 - Energy Calculation Summary

ARRAY TYPE	SITE LOCATION	TOTAL IRRAD. $\frac{kWh}{m^2/yr}$	ACTUAL ARRAY OUTPUT $\frac{kWh}{m^2/yr}$	$\eta(T_r, S_r) \int_{yr} S\,dt \Big/ \int_{yr} S(t)\eta(T)\,dt$ FIXED ENVIRONMENT T = 20 S = 80	FIXED ENVIRONMENT T = 15 S = 100	FIXED CELL TEMP. T = 25 S = 100	FIXED CELL TEMP. T = 45 S = 100
AVG. FLAT PLATE	ALBUQ.	2316	248	1.00	1.00	1.10	1.00
	CAP. HAT.	1832	196	0.99	1.01	1.14	1.04
	OMAHA	1853	201	0.99	0.99	1.09	1.01
	MIAMI	1895	196	1.03	1.04	1.14	1.04
AVG. 2-AXIS CON.	ALBUQ.	2552	274	0.99	1.00	1.10	1.00
	CAP. HAT.	1512	162	0.99	1.01	1.11	1.00
	OMAHA	1638	177	0.99	0.99	1.10	0.99
	MIAMI	1372	142	1.03	1.04	1.15	1.04
HOT 2-AXIS CON.	ALBUQ.	2552	252	1.00	0.98	1.20	1.09
	CAP. HAT.	1512	152	0.97	0.97	1.18	1.08
	OMAHA	1638	166	0.97	0.95	1.17	1.06
	MIAMI	1372	134	1.01	0.99	1.22	1.10

T: CELL/AIR TEMPERATURE, (°C), S: IRRADIANCE, (mW/cm^2)

the hourly SOLMET data, and an additional two-axis-tracking array with a higher operating temperature was added.

Table 2 compares the accuracy obtained for the annual energy output using various fixed temperature and fixed environment reference conditions. As can be seen, the fixed environmental condition of (80 mW cm^{-2}, 20°C air, 1 m s^{-1} wind) provides the best accuracy with a maximum error of only 3% for all site locations, array tracking, and thermal designs. The other environmental condition leads to a slightly larger error, and the fixed temperature conditions lead to very large errors.

4. CONCLUSIONS

In addition to providing a repeatable reference for performance comparisons, it has been shown that the choice of reference conditions directly controls the accuracy of array energy output prediction calculations. Examination of the commonly used air mass 1.5 reference solar irradiance spectrum indicates that it provides reasonable accuracy for energy prediction for both concentrator and flat-plate arrays. However, the spectrum which provides the least error for flat-plate arrays is the spectral distribution of annual irradiant energy as shown in Fig 1.

In the analysis of cell temperature and irradiance level reference conditions it has been shown that the concept of a reference environmental condition provides an efficient means of including the effect of a module's thermal design on its electrical performance. The concept of a Nominal Operating Cell Temperature (NOCT) derives from the reference environmental condition and serves in place of the usual cell reference temperature which is fixed for all designs. The use of a well chosen environmental reference condition is shown to provide an efficient and accurate means of computing the annual energy output for both flat-plate and concentrating arrays, independent of the site location and the array's thermal design.

5. REFERENCES

(1) Stultz, J.W. and Wen, L.C., "Thermal Performance Testing and Analysis of Photovoltaic Modules in Natural Sunlight," Jet Propulsion Laboratory, Report 5101-31, July 29, 1977.

(2) "Revised Terrestrial Photovoltaic Measurement Procedures," NASA Lewis Research Center, NASA TM 73702, June 1977.