ENERGY PREDICTION USING NOCT-BASED PHOTOVOLTAIC REFERENCE CONDITIONS*

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ABSTRACT

With the growing introduction of various thin-film solar-cell modules into the photovoltaic marketplace, the appropriateness of conventional power-output ratings at a fixed irradiance level, solar spectrum, and cell temperature has been the subject of increasing debate. At issue is the ability of various nameplate power ratings to reflect accurately the site-specific energy generation potential of devices with widely different current-voltage (I-V curve) characteristics.

This paper examines critically the energy prediction ability of rating conditions based on Nominal Operating Cell Temperature (NOCT) and presents two approaches to fine-tuning this rating system for site-specific ambient temperature and I-V fill factor. One modification provides site-specific rating conditions (irradiance and air temperature) and the other provides site ambient temperature and fill-factor based corrections to the standard NOCT-based (80 mW/cm^2, 20°C ambient temperature) power output rating. The study results indicate that the standard NOCT-based power rating provides good energy prediction ability for sites with moderate climates. The modifications provide two approaches for high-accuracy fine tuning of the energy prediction for any site and fill factor, based on readily available weather-atlas parameters.

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1. INTRODUCTION

The Jet Propulsion Laboratory's (JPL) Flat-Plate Solar Array Project (FSA) has primary responsibility within the Department of Energy's National Photovoltaics Program for managing research related to flat-plate photovoltaic solar arrays. Research on array performance criteria and measurement methods is an active part of the FSA effort and supports indirectly the photovoltaic standards activities of various consensus standards organizations, such as ASTM, IEEE, and IEC.

An important concern of the photovoltaic community is the applicability of historical photovoltaic power-output rating schemes to the new generations of photovoltaic modules involving thin-film solar cells. Of particular interest is the ability of existing power ratings to characterize accurately their energy generation potential, which is the most relevant performance measure of a photovoltaic array.

A key factor affecting the relationship between power rating and energy performance is the fill factor of the array's current-voltage (I-V) curve. Fill factor is defined as the ratio of maximum power to the product of short-circuit current and open-circuit voltage, and is a measure of the squareness of the I-V curve. At issue is the fact that an array with a low fill factor (e.g., 0.6) generates less energy over a year than an array with a high fill factor (e.g., 0.75) with the same power nameplate rating at the standard reporting conditions of 100 mW/cm^2.

The systematic development of photovoltaic rating conditions related to energy performance has been addressed by these authors in a previous paper, and led to the concept of rating power at an array's Nominal Operating Cell Temperature (NOCT) (Ref. 1). This concept works well to normalize the effects of varying array thermal characteristics and is modestly

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insensitive to fill factor when the power is rated at (80 mW/cm^2, NOCT). Site- and array-specific energy production was shown to be well approximated by the product of the array's efficiency at 80 mW/cm^2, NOCT, and the integrated solar irradiance incident on the array at the site of interest (Ref. 1). However, because NOCT is a fixed number for any array, site-specific ambient-temperature and fill-factor dependencies are not specifically addressed. These shortcomings have been the subject of recent comment (Ref. 2).

This paper first provides a detailed assessment of the energy prediction accuracy of the NOCT method, and then presents two approaches to fine-tuning the method to include site-specific ambient temperature and fill-factor dependencies.

2. COMPUTATION OF BASELINE ENERGY PRODUCTION

To assess the accuracy of any simplified energy prediction algorithm, it is first necessary to establish the true, or baseline, energy production for a chosen set of representative arrays and sites using a method with known high accuracy. For the purposes of this study, the baseline energy output is assumed to be accurately defined by integrating the hourly power generation predicted for a fixed-latitude-tilt array using measured site weather data and measured array response to weather parameters. The absolute accuracy of the site weather data is not particularly important as long as it is representative, and reflects typical irradiance-level, ambient-temperature interrelationships. SOLMET typical meteorological year (TMY) data tapes were used in this study and provide a convenient source of hourly data for 26 sites in the United States with diverse climates.

In equation form, the baseline annual energy from an array is given by:

$$E_{yr} = \int_{yr} S(t)\ \eta(t)\ dt \qquad (1)$$

where:

E_{yr} = annual energy output per unit array area, Whm^{-2}
$S(t)$ = total (pyranometer) irradiance at time (t), Wm^{-2}
$\eta(t)$ = array efficiency at S(t) and T(t)
$T(t)$ = cell temperature at time (t), °C

A critical element of the implementation of equation (1) is the accurate computation of the array efficiency at the various hourly combinations of ambient temperature and irradiance level. This is accomplished by first computing the hourly solar cell temperature from the hourly irradiance, ambient temperature and wind data using the experimentally derived relationship (Ref.3):

$$T_{cell} = T_{air} + (k - 0.01V)\ S \qquad (2)$$

where

T_{cell} = Cell temperature, °C
T_{air} = Ambient temperature, °C
V = Wind Velocity, ms^{-1}
S = Irradiance level, mW cm^{-2}
k = Empirical constant characterizing the thermal resistance of the array of interest.

Next, the array I-V curve, and thence hourly maximum power, is computed for each hourly combination of irradiance level and cell temperature using I-V curve translation equations that model accurately the temperature-irradiance behavior of the array of interest. This step requires particular care because available translation algorithms are derived based on the behavior of a single solar cell, and only model the behavior of an array when all array elements are perfectly matched with identical I-V curves.

When all elements are matched, the I-V curve translates with irradiance level without changing shape significantly, as shown in Fig. 1. However, if one or more elements are mismatched, the shape of the I-V curve may be significantly altered by the mismatched elements and will change with variation in irradiance. Fig. 2 illustrates the measured effect of a single mismatched cell on the I-V curve of a photovoltaic module at various irradiance levels. Notice that the I-V curve shape approaches the unaltered shape as the irradiance level is reduced. This non-linear behavior significantly complicates the prediction of the energy performance of electrically mismatched arrays, and to our knowledge is not treated by any available I-V translation models.

For the purpose of this study, a perfectly matched array was assumed, and fill factor was treated parametrically using values of

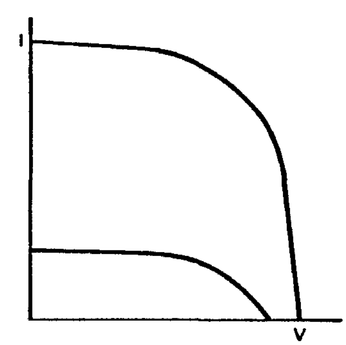

Fig. 1. Translation of Photovoltaic I-V Curve with Changes in Irradiance Level at Constant Temperature

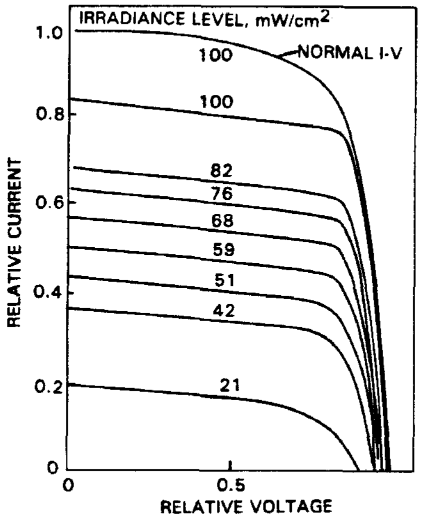

Fig. 2. Translation of Single-Point-Failure I-V Curve with Change in Irradiance Level at Constant Temperature

0.60, 0.65, 0.70 and 0.75 at 100 mW/cm^2, 25°C. Arrays of different thermal designs were similarly included using parametric thermal constants (k = 0.325 and 0.45). These thermal constants correspond to modules with NOCT values of 46°C and 56°C, respectively. To provide a diversity of climatic extremes, eleven SOLMET sites were utilized; these were: Albuquerque, NM; Bismarck, ND; Boston, MA; Columbia, MO; Dodge City, KS; Fresno, CA; Great Falls, MT.; Miami, FL; Omaha, NB; Phoenix, AZ; and Santa Maria, CA.

3. SIMPLIFIED ENERGY PREDICTION ALGORITHMS

Because hour-by-hour weather data are available for only a very limited number of site locations, there is need for a simplified algorithm suitable for approximating photovoltaic energy production accurately based on summary data such as monthly average weather-atlas values. One such simplified algorithm is of the form (Ref. 1):

$$E_p = \eta(T_r, S_r) \int_p S(t)dt \qquad (3)$$

where

E_p = array energy output over period p

η = array efficiency at reference ambient temperature (T_r) and reference irradiance level (S_r)

$\int_p Sdt$ = integrated irradiance over period p for the site and array tracking geometry of interest

For the NOCT-based algorithm, the reference irradiance level (S_r) is 80 mW/cm^2, and the reference ambient temperature (T_r) is 20°C. These values of S_r and T_r were chosen to minimize the energy prediction error for typical arrays with fill factors around 0.7 and sites with moderate climates.

In the present study, Equations (2) and (3) were used to examine the accuracy of the NOCT baseline algorithm for an extensive variety of test cases involving a fixed-latitude-tilt flat-plate array with the site locations, fill factors and thermal characteristics noted above. The hourly irradiance level on the array was derived from the SOLMET irradiance data by using an algorithm developed by T. Klucher, based on the work of B. Liu and R. Jordan (Ref. 1). In addition, site specific values of S_r and T_r were derived based on minimizing the energy error for each site over the range of fill factors (0.60, 0.65, 0.70, 0.75) and thermal characteristics (k = 0.325 and 0.45).

Figure 3 displays the site-specific optimum reference conditions for each of the eleven sites together with the conditions that led to the lowest energy prediction error for all eleven sites simultaneously. Several observations can be drawn from these data:

(1) The "best-compromise" reference condition is given by an ambient air temperature of 20°C and an irradiance level of 65 mW/cm^2.

(2) The optimum ambient-temperature and irradiance-level reference condition varies widely with site location.

(3) It would be useful to correlate the site specific reference conditions with generic weather-atlas data such as mean daily maximum temperature and cloudiness indicators.

(4) The absolute energy-prediction error for any given set of conditions needs to be examined.

Based on the above observations, the site-specific reference conditions were cross-correlated with several site-specific

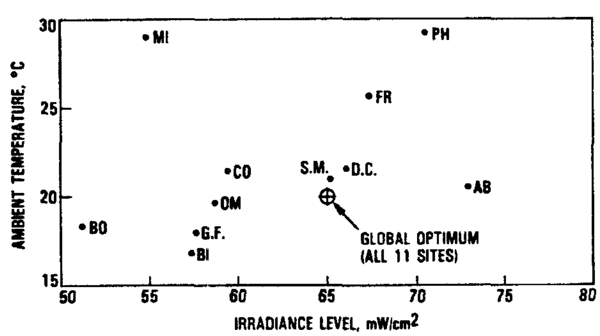

Fig. 3. Optimum Site-Specific Reference Conditions for SOLMET Sites Listed in Text

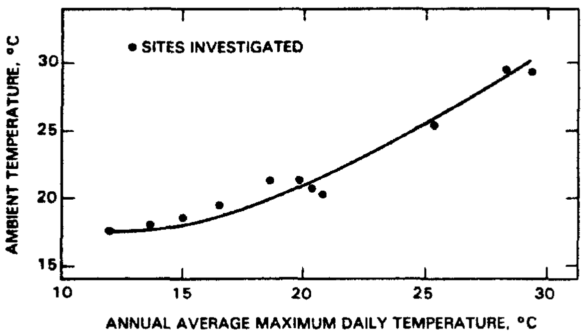

Fig. 4. Optimum Reference Ambient Temperature as a Function of Site Annual Maximum Daily Temperature

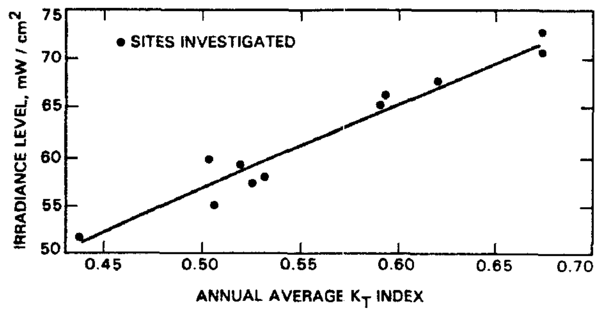

Fig. 5. Optimum Reference Irradiance Level as a Function of Site Annual Average K_T Index

temperature and irradiance indices. The best results were obtained by correlating the optimum reference ambient temperature with the site annual average maximum daily temperature, and by correlating the optimum reference irradiance level with the average annual K_T index. The K_T index is the ratio of the total daily radiation on a horizontal surface at ground level, divided by the total daily extraterrestrial radiation on a horizontal surface. Average daily maximum temperatures can be found in any climatic atlas, such as Reference 4; the K_T indices for a great number of sites are provided in Reference 5. Figures 4 and 5 provide a graphical representation of these two correlations.

To provide a quantitative evaluation of each of the various candidate reference conditions, the relative energy prediction error was computed for a variety of sites, thermal characteristics and fill factors. Table 1 summarizes some of these values and leads to the following additional observations:

(1) The baseline 80 mW/cm^2, 20°C reference condition provides good accuracy for high fill factors and moderate climates.

(2) The optimized 65 mW/cm^2, 20°C condition leads to improved energy prediction, but site-specific errors remain as high as $\pm 5\%$.

(3) The site-specific reference conditions based on atlas temperatures and K_T values provide excellent energy prediction, with less than 1% error for all cases.

Observing that the optimized reference conditions lead to only a modest improvement over the baseline NOCT values, it seems appropriate to examine the concept of a site and fill-factor-dependent correction that can be used to fine-tune the NOCT energy predictions for low fill factors and climates with extreme temperatures. To this end, Figures 6 and 7 provide multiplicative correction factors $\phi(T)$ and $\psi(K_T)$ correlated against site annual average maximum daily temperature (T) and annual average K_T index. The resulting energy prediction algorithm is therefore of the form:

$$E_p = \phi(T)\left[1-\psi(K_T)(0.7-FF)\right] E_{NOCT} \quad (4)$$

where E_{NOCT} is defined by equation (3) with T_r=20°C and S_r=80 mW/cm^2, and FF is the array I-V fill factor.

The absolute prediction errors associated with Equation 4 and the relationships in Figures 6 and 7 are displayed in the right-hand column of Table 1. Although not as accurate as the site specific reference conditions, this correction-factor approach also offers excellent site-specific energy prediction.

4. CONCLUSIONS

Review of the NOCT-based energy prediction algorithm indicates that it does a good job of energy prediction for high-fill-factor arrays in moderate climates, but over-predicts the energy of low-fill-factor arrays in hot climates by a few percentage points. Attempts to locate a single temperature-irradiance condition with improved accuracy at low fill factors was only partially successful because of resulting reduced accuracy for high-fill-factor arrays in moderate climates.

If improved accuracy beyond the generic NOCT-based algorithm is desired, it appears that a site-specific approach is needed. Two approaches, one based on a site-specific reference condition, and the other based on a site and fill-factor adjustment of the NOCT-baseline condition, have been developed. Both site-specific approaches have been correlated to readily available weather atlas data and provide excellent energy prediction accuracy with errors typically less than 1%.

Although the site-specific algorithms have

TABLE 1. DEVIATIONS IN ENERGY CALCULATION FROM BASELINE

Site Site Ref. Cond. $S(mWcm^{-2}):T(^{o}C)$	Fill Factor	NOCT (^{o}C)	$\eta(T_r,S_r)\int_{yr} S(t)\,dt \Big/ \int_{yr} S(t)\,\eta(T,S)\,dt$			
			$S=80\ mWcm^{-2}$ $T=20^{o}C$	$S=65\ mWcm^{-2}$ $T=20^{o}C$	Site Spec. Ref. Conditions	S=80:T=20 plus Correct. Factor
Albuquerque, NM S=71.4:T=21.4	0.70	46	1.002	0.998	0.993	0.994
	0.60	46	1.011	0.989	0.991	0.992
	0.70	56	1.001	1.008	0.998	0.993
	0.60	56	1.009	0.998	0.995	0.990
Bismarck, ND S=58.7:T=17.5	0.70	56	0.977	0.983	0.998	1.000
	0.60	56	1.003	0.992	0.999	0.995
Boston, MA S=51.0:T=18.2	0.70	46	1.003	0.999	0.997	1.016
	0.60	46	1.044	1.021	0.998	1.012
	0.70	56	0.989	0.996	0.996	1.002
	0.60	56	1.027	1.015	0.996	0.996
Columbia, MO S=56.5:T=19.9	0.70	56	1.003	1.009	1.010	1.003
	0.60	56	1.031	1.019	1.008	0.996
Dodge City, KS S=64.5:T=20.7	0.70	56	1.004	1.010	1.006	1.000
	0.60	56	1.021	1.009	1.004	0.995
Fresno, CA S=66.7:T=25.9	0.70	56	1.028	1.035	1.001	1.006
	0.60	56	1.047	1.035	0.999	1.007
Great Falls,MT S=59.2:T=17.7	0.70	56	0.989	0.990	1.003	1.002
	0.60	56	1.010	0.995	1.005	0.996
Miami, FL S=57.0:T=29.0	0.70	46	1.060	1.056	0.999	1.009
	0.60	46	1.106	1.081	0.995	1.017
	0.70	56	1.050	1.056	0.997	1.000
	0.60	56	1.091	1.079	0.994	1.003
Omaha, NE S=58.1:T=18.8	0.70	46	1.002	0.998	1.000	1.009
	0.60	46	1.032	1.009	1.001	1.006
	0.70	56	0.994	1.000	1.007	1.001
	0.60	56	1.020	1.008	1.006	0.994
Phoenix, AZ S=71.4:T=30.0	0.70	46	1.050	1.046	0.993	0.995
	0.60	46	1.070	1.046	0.995	1.003
	0.70	56	1.051	1.058	0.997	0.996
	0.60	56	1.069	1.057	0.997	1.002
Santa Maria, CA S=64.2:T=21.0	0.70	56	1.001	1.008	1.002	0.995
	0.60	56	1.019	1.008	1.001	0.990

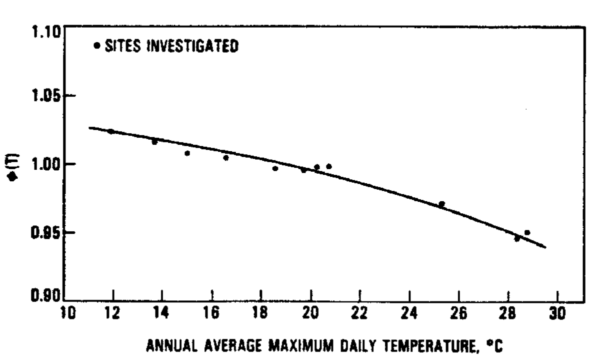

Fig. 6. Ambient Temperature Correction Factor $\phi(T)$ as a Function of Site Annual Average Maximum Daily Temperature

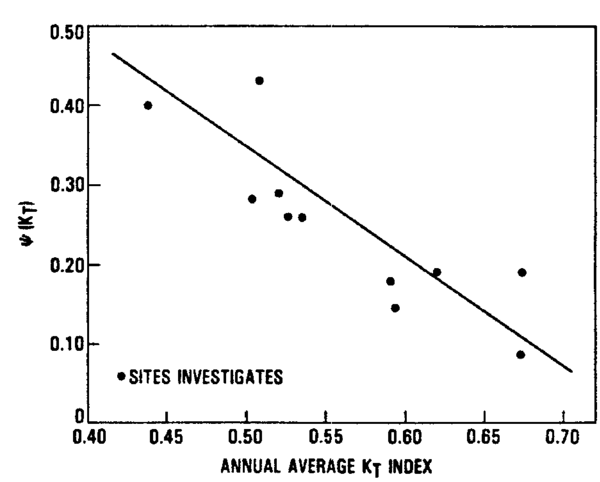

Fig. 7. Cloudiness Correction Factor $\psi(K_T)$ as a Function of Site Annual Average K_T Index

not been tested as predictors of monthly energy output, it is expected that both will also provide an effective means of predicting monthly energy production based on monthly irradiance, ambient temperature and K_T data.

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