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CHARACTERIZATION OF PHOTOVOLTAIC ARRAY PERFORMANCE: AN OVERVIEW*

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1. Introduction

Characterization of the electrical performance of a photovoltaic array can take many forms depending on the end use of the data. Typical uses include buyer-seller negotiations, system performance prediction, and performance measurement.

Buyer-seller negotiations may deal with specifying the size (power) of an array to be purchased under some standard reporting conditions, and may treat the warranty conditions governing allowable degradation of this performance with time. System design, on the other hand, requires prediction of performance under varying field conditions, not standard reporting conditions, and must include the non-ideal realities of operating systems: array shadowing, steep angles of incidence, soiling, and array-load energy utilization. Typical uses of predicted array performance include array sizing tradeoffs, tracking-pointing comparisons, load-array interface analyses and system economic evaluations. The third use, performance measurement, refers to the characterization of an as-built array as opposed to prediction of the performance of an array to be built. This may be done to assess actual array performance or to measure performance degradation over time.

2. Array performance rating conditions

In response to these varying uses, an array's performance can be described in terms of an instantaneous power output under some given environmental or standard reporting conditions, or can be articulated as a site-specific energy output over a period of time, such as a day, month or year.

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Because the array's I-V performance is a strong function of irradiance level and cell temperature (see Fig. 1), the output of an array is generally quantified by its current-voltage (I-V) curve corresponding to a chosen set of standard reporting conditions. Standard conditions of 100 mW cm^{-2} irradiance, air mass 1.5 spectrum, and 25 °C cell temperature are often used to specify the size of a given array.

In place of the 25 °C cell temperature a module's nominal operating cell temperature (NOCT) is sometimes used; this is the temperature the cells reach under standard average environmental conditions of 80 mW cm^{-2} irradiance, 20 °C air temperature and 1 m s^{-1} wind velocity. Figure 2 illustrates the fraction of annual energy generated by a typical photovoltaic array during operating periods when the cell temperature is greater than the abscissa value. Note that approximately equal amounts of the energy are generated during operating periods when the cell temperature is above and below NOCT, and that about 70% is generated within 10 °C of NOCT. Because NOCT is a good representation of the mean temperature of an array during periods of significant energy generation, the annual energy output of an array is well approximated by the product of its efficiency at 100 mW cm^{-2}, NOCT and the site-specific annual irradiance incident on the array in kW h year^{-1} [1, 2].

Although an array's annual energy performance is approximated quite well by the above NOCT relationship, there are circumstances that can cause the energy performance of two equal power arrays to be different. Figure 3 illustrates how two arrays with equal power at high irradiance levels can have different powers at low irradiance levels. Such differences have led to the advocacy of module energy ratings to more correctly reflect the energy merit of competing arrays [3]. Energy ratings, however, have not achieved

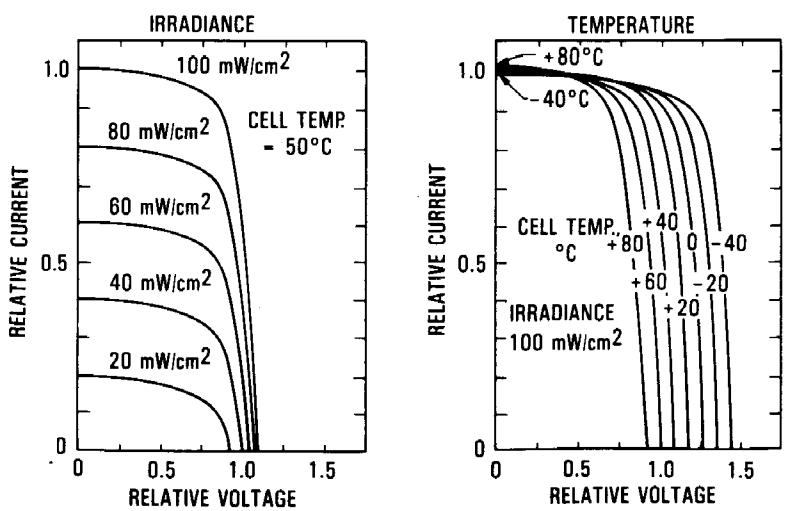

Fig. 1. Typical performance dependence for crystalline-silicon modules.

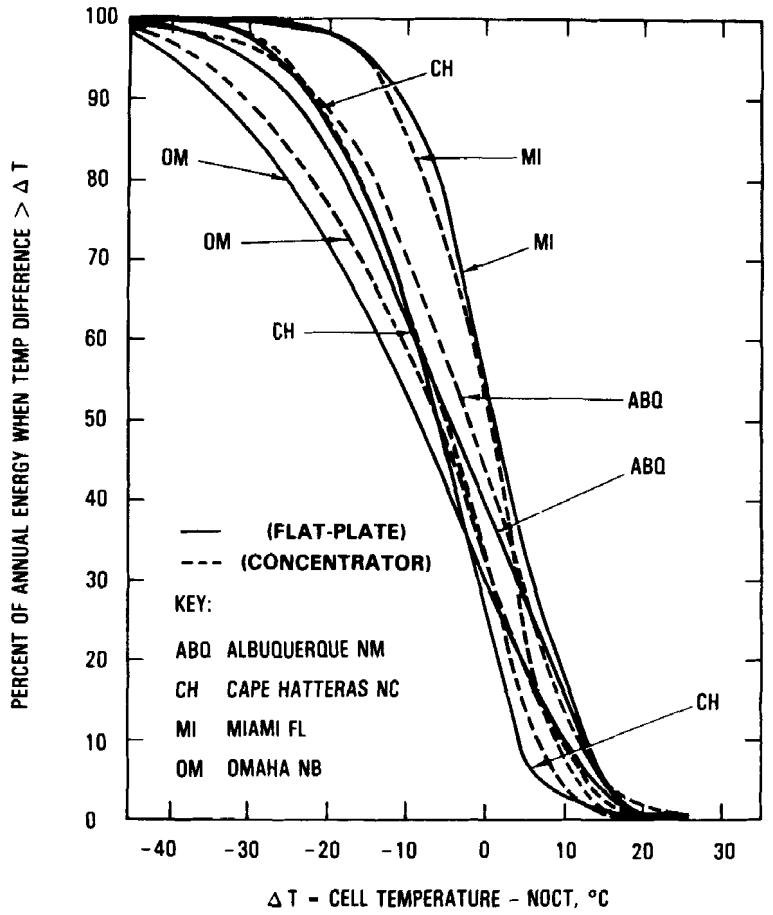

Fig. 2. PV electrical energy generation *vs.* cell temperature.

widespread use, partially because small systems are generally sized by A h performance, not energy performance, and large systems, which are sized by energy performance, justify accurate characterization via large hourly simulation models that include load-interface considerations.

3. Array performance prediction

An important use of array performance data is in photovoltaic system design including array sizing tradeoffs, tracking-pointing comparisons, array-load interface analyses, energy performance computations, and economic analyses. Such design analyses are often based on hourly simulation of the array and system output over the course of a year or more. For each hour of the year the instantaneous performance of the array is

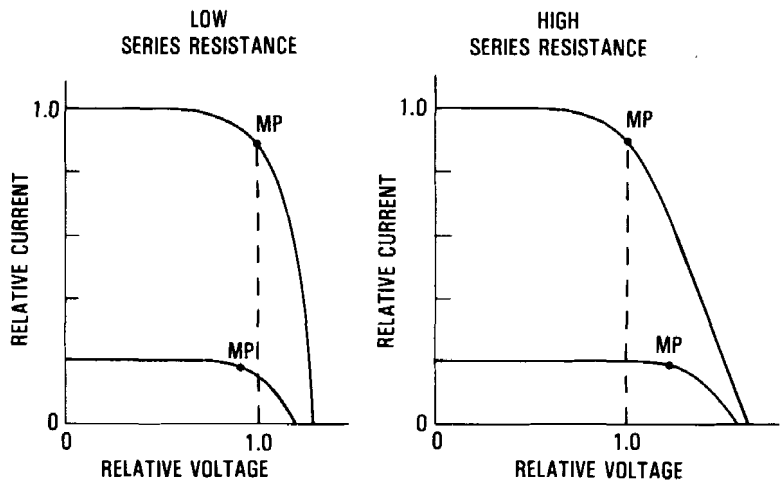

Fig. 3. Effect of series resistance on power output at high (100 mW cm^{-2}) *vs.* low (20 mW cm^{-2}) irradiance levels.

computed based on available data for irradiance level, air temperature, wind velocity and system state, such as battery state of charge. The irradiance, air temperature, and other meterological parameters are generally obtained from historical weather data such as SOLMET TMY data tapes [4, 5].

To compute an array's instantaneous performance requires first combining the module *I-V* curves at standard reporting conditions (100 mW cm^{-2}, 25 °C) to obtain the ideal array *I-V* curve at these same conditions. This is done by multiplying the module *I-V* current times the number of modules in parallel, and multiplying the module voltage times the number of modules in series. To obtain the array's ideal *I-V* curve under different environmental conditions one must use translation equations that adjust for the influence of the changed irradiance level and/or cell temperature [6]. Although the translation equations are different for different cell types (crystalline-Si, amorphous-Si, CdTe, etc.) generally the current is shifted proportional to the incident irradiance, and the voltage is shifted (reduced) by increased temperature (approx. 2.2 mV °C^{-1} per series solar cell for crystalline-Si).

The instantaneous irradiance level incident on the tilted array surface is determined with appropriate irradiance sky models [7, 8] and the cell operating temperature is determined using available thermal models [9]. For flat-plate collectors the temperature is well approximated as

$$T_{\text{cell}}\ (^\circ\text{C}) = T_{\text{air}}\ (^\circ\text{C}) + ((\text{NOCT-20})\ /80)\ S$$

where S is the incident irradiance level (mW cm^{-2}). Figure 4 illustrates this linear temperature dependence on ambient temperature and incident irradiance level.

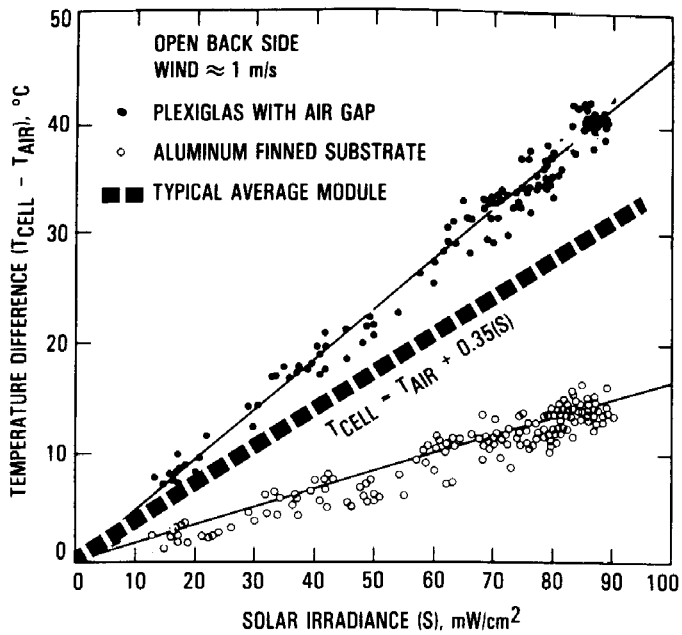

Fig. 4. Thermal performance of flat-plate photovoltaic modules.

To compute the actual *I-V* curve for an array one must next account for a number of array losses that represent non-ideal behavior of the array. These include electrical mismatch due to non-identical modules and non-uniform irradiance (partial shadowing), transmission losses due to soiling and increased reflectance at steep angles of incidence, array wiring resistance losses, and blocking-diode voltage drops [10]. Although the effect of electrical mismatch is complex and difficult to compute, the remaining losses are readily introduced into the array *I-V* curve using available translations for irradiance level, voltage drops and series resistance.

A final consideration when computing system performance to array energy output is the instantaneous operating point on the array's *I-V* curve [11, 12]. Maximum energy is generated by a system whose load impedence dynamically varies to ideally match the array's maximum power point under all conditions. Such a load is said to be "maximum power tracking". A properly selected constant-voltage load such as a battery provides excellent maximum power tracking and minimal energy losses. Impedence matching losses can be very large for non-optimal loads such as resistance or motor loads.

A second load-matching consideration is minimum or maximum voltage, current or power constraints imposed by the load. Often a load cannot operate below some threshold voltage or power level, or will reject power under conditions of high array output. These load-matching factors must be treated on a case-by-case basis [11, 12].

4. Array performance measurement

After an array is fabricated and installed it is often desired to characterize the achieved performance, either as-built, or following a period of field aging. To allow meaningful interpretation of the measured performance, it is common practice to convert the real-time data to a performance at standard reporting conditions, typically 100 mW cm^{-2}, AM 1.5 spectrum, 25 °C cell temperature. This requires accurate determination of the irradiance level and cell temperature at the time of measurement and reversing the normalization (curve translation) procedures as described under performance prediction.

A number of sources of error enter into this process and demand great care in measurement technique to achieve ±5% accuracy. Critical elements of the process include measuring the irradiance level, cell temperature, and variable loss mechanisms.

4.1. Measuring irradiance

Accurate measurement of the irradiance level and its spectrum is very important to allow correction back to the reference-level irradiance (100 mW cm^{-2}, AM 1.5 spectrum). One technique is to use a precision pyranometer (typically ± 5% accuracy) together with a spectral radiometer to measure the relative spectrum; then to use a spectral mismatch factor to correct the measured performance back to the AM 1.5 reference spectrum [13]. The modest accuracy of available pyranometers, particularly when used tilted, is a critical limitation.

The second, and preferred technique, is to measure the effective irradiance level with a precision reference solar cell (±1% accuracy) having a spectral response close to that of the measured array. The output of the reference cell is, by the nature of its calibration, already converted to equivalent irradiance at the reference spectrum.

Another important consideration when measuring irradiance incident on the array is recognizing that the level can easily vary as much as ±5% over the array area due to non-uniform reflected light from the ground and surrounding structures, and due to non-uniform blockage of the diffuse sky light (diffuse shadows). Accurate measurements require highly uniform (±1%) irradiance distributions over the area of the array to avoid electrical mismatch effects. In addition, the location of the irradiance-measurement instrument must be carefully chosen to measure the average irradiance in the plane of the array.

4.2. Measuring cell temperature

Accurate measurement of cell temperature is fraught with similar problems. Because the solar cells themselves are generally inaccessible, their temperature must often be inferred from measurements of module rear-surface temperature using thermocouples positioned behind the cells. The cell temperature is then extrapolated from this rear-surface temperature using empirically established relationships for the temperature drop from cell

to rear surface as a function of irradiance level. Care must be exercised to ensure that the temperature sensor is accurately measuring the rear-surface temperature and is not being influenced by such things as heat conduction down its electrical leads. This is particularly troublesome when the module rear surface is a poor thermal conductor.

As with non-uniform irradiance, non-uniform temperature over the array area is also troublesome; this is generally caused by increased cooling of the outer edges and the lower edge of the array, by non-uniform irradiance on the front and rear (from reflected light) surfaces, and by non-uniform view factors of sky, illuminated ground, and shaded ground.

4.3. Establishing status of array loss mechanisms

Although many array losses, such as I^2R wiring losses, are an integral part of the array, other losses are highly variable and must be defined if the measured array performance is to have meaning. Front surface soiling is an obvious example and is often normalized by washing the array prior to measurement. Other effects include reflection losses at large off-normal angles of incidence, and electrical mismatch caused by non-uniform irradiance and/or temperature over the array area. These are usually dealt with by trying to achieve uniform irradiance and an angle of incidence within 20° of normal.

5. Conclusions

The variety of uses of array performance data, for buyer–seller interfaces, array design and *in situ* verification, place different demands on data quality and format. Buyer–seller interfaces and *in situ* verification generally utilize performance specified at recognized standard reporting conditions (generally 100 mW cm^{-2}, AM 1.5 spectrum, 25 °C cell temperature). On the other hand, system and array design require parametric performance data over the expected range of field operating conditions.

The process of determining performance can be founded on analytical prediction from module data and environmental estimates, or on *in situ* measurement of an as-built array. Both approaches have a number of elements in common: (1) determining irradiance level (and uniformity); (2) determining cell temperature (and variation); (3) characterization of array loss mechanisms; (4) selection of performance reporting conditions; (5) translating performance to desired conditions. With careful attention to detail, the available techniques provide performance characterization accuracies of around ±5%, which is sufficient for most needs.

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References

1 R. G. Ross, Jr. and C. C. Gonzalez, Reference conditions for reporting terrestrial photovoltaic performance, *Proc. Annu. Meet. AS/ISES, Phoenix, AZ, 1980*, pp. 1091 - 1097.

2 C. C. Gonzalez and R. G. Ross Jr., Energy prediction using NOCT-based photovoltaic reference conditions, *Proc. Annu. Am. Sol. Energy Soc. Conf., June 1 - 3, 1983, Minneapolis, MN.*

3 C. F. Gay, AM - PM: all day module performance measurements, *Proc. 16th IEEE Conf. Photovoltaic Specialists* (1982) 1041 - 1046.

4 SOLMET, User's Manual, Hourly solar radiation-surface meteorological observations, Vol. 1 *TD-9724*, December 1977, available from National Oceanic and Atmospheric Administration, Asheville, NC, U.S.A.

5 SOLMET, Final Rep., Hourly solar radiation-surface meteorological observations, Vol. 2 *TD-9724*, February 1979, available from National Oceanic and Atmospheric Administration, Asheville, NC.

6 J. D. Sandstrom, A method for predicting solar cell current-voltage characteristics as a function of incident solar intensity and cell temperature, *Proc. 6th IEEE Conf. Photovoltaic Specialists* (1967) 199 - 208.

7 T. M. Klucher, Evaluation of models to predict insolation on tilted surfaces, *Sol. Energy, 23* (1979) 111 - 114.

8 R. R. Perez, J. T. Scott and R. Stewart, An anisotropic model for diffuse radiation incident on slopes of different orientations and possible applications to CPCs, *Proc. Annu. Meet. AS/ISES, June 1 - 3, 1983, Minneapolis, MN*, pp. 883 - 888.

9 L. Wen, Thermal performance of residential photovoltaic arrays, *Proc. Am. Sol. Energy Soc. Conf., June 5 - 9, 1984, Anaheim, CA.*

10 C. Gonzalez, Photovoltaic array loss mechanisms, *Proc. Photovoltaics and Insolation Measurements Workshop, June 30 - July 3, 1985, Vail, CO*, SERI/CP-215-2773, DE-850-12145, Solar Energy Research Institute, Golden, CO, U.S.A., 1985.

11 C. C. Gonzalez, G. M. Hill and R. G. Ross, Jr., Photovoltaic array-power conditioner interface characteristics, *JPL Publ. 82-109, JPL Document 5101-202, DOE/JPL-1012-79*, Jet Propulsion Laboratory, Pasadena, CA, U.S.A., 1982.

12 C. C. Gonzalez, G. M. Hill and R. G. Ross, Jr., Photovoltaic array-power conditioner interface requirements, *Proc. Annu. Meet. AS/ISES, Houston, TX*, pp. 909 - 914.

13 C. H. Seaman, The correction for spectral mismatch effects on the calibration of a solar cell when using a solar simulator, *JPL Publ. 81-1, JPL Document 5101-169, DOE/JPL-1012-50*, Jet Propulsion Laboratory, Pasadena, CA, U.S.A., January 1981.