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Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells [1]

This standard is issued under the fixed designation E 1036; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 These test methods cover the electrical performance of photovoltaic modules and arrays under natural or simulated sunlight using a calibrated reference cell.

1.1.1 These test methods allow a reference module to be used instead of a reference cell provided the reference module has been calibrated using these test methods against a calibrated reference cell.

1.2 Measurements under a variety of conditions are allowed; results are reported under a select set of reporting conditions (RC) to facilitate comparison of results.

1.3 These test methods apply only to nonconcentrator terrestrial modules and arrays.

1.4 The performance parameters determined by these test methods apply only at the time of the test, and imply no past or future performance level.

1.5There is no similar or equivalent ISO standard.

1.6

1.5 These test methods apply to photovoltaic modules and arrays that do not contain series-connected photovoltaic multijunction devices; such module and arrays should be tested according to Test Methods E 2236.

1.6 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E 772 Terminology Relating to Solar Energy Conversion

E 927 Specification for Solar Simulation for Photovoltaic Testing

E 941 Test Method for Calibration of Reference Pyranometers With Axis Tilted by the Shading Method

E 948 Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight

E 973 Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell

E 1021 Test Method for Spectral Responsivity Measurements of Photovoltaic Devices

E 1039 Test Method for Calibration of Silicon Non-Concentrator Photovoltaic Primary Reference Cells Under Global Irradiation

E 1040 Specification for Physical Characteristics of Nonconcentrator Terrestrial Photovoltaic Reference Cells

E 1125 Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum

E 1328 Terminology Relating to Photovoltaic Solar Energy Conversion

E 1362 Test Method for Calibration of Non-Concentrator Photovoltaic Secondary Reference Cells

G159Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test

[1] These test methods are under the jurisdiction of ASTM Committee E44 on Solar, Geothermal and Other Alternative Energy Sources and are the direct responsibility of Subcommittee E44.09 on Photovoltaic Electric Power Conversion.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

E 2236 Test Methods for Measurement of Electrical Performance and Spectral Response of Nonconcentrator Multijunction Photovoltaic Cells and Modules
G 173 Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37 Tilted Surface

3. Terminology

3.1 *Definitions*—Definitions of terms used in these test methods may be found in Terminology E 772 and Terminology E 1328.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *nominal operating cell temperature, NOCT*, *n*—the temperature of a solar cell inside a module operating at an ambient temperature of 20°C, an irradiance of 800 Wm^{-2}, and an average wind speed of 1 ms^{-1}.

3.2.2 *reporting conditions, RC*, *n*—the device temperature, total irradiance, and reference spectral irradiance conditions that module or array performance data are corrected to.

3.3 *Symbols:*

3.3.1 The following symbols and units are used in these test methods:

α_r—temperature coefficient of reference cell I_{SC}, $°C^{-1}$,
α—current temperature coefficient of device under test, $°C^{-1}$,
$\beta(E)$—voltage temperature function of device under test, $°C^{-1}$,
C—calibration constant of reference cell, Am^2W^{-1},
C'—adjusted calibration constant of reference cell, Am^2W^{-1},
C_f—NOCT Correction factor,°C,
$\delta(T)$—voltage irradiance correction function of device under test, dimensionless,
ΔT—NOCT cell-ambient temperature difference, °C,
E—irradiance, Wm^{-2},
E_o—irradiance at RC, Wm^{-2},
FF—fill factor, dimensionless,
I—current, A,
I_{mp}—current at maximum power, A,
I_o—current at RC, A,
I_r—short-circuit current of reference cell, A, —short-circuit current of reference cell (or module, see 1.1.1 and 4.3.4), A,
I_{sc}—short-circuit current, A,
M—spectral mismatch parameter, dimensionless,
P—electrical power, W,
P_m—maximum power, W,
T—temperature, °C,
T_a—ambient temperature, °C,
T_c—temperature of cell in module, °C,
T_o—temperature at RC, °C,
T_r—temperature of reference cell, °C,
ν—wind speed, ms^{-1},
V—voltage, V,
V_{mp}—voltage at maximum power, V,
V_o—voltage at RC, V, and
V_{oc}—open-circuit voltage, V.

4. Summary of Test Methods

4.1 Measurement of the performance of a photovoltaic module or array illuminated by a light source consists of determining at least the following electrical characteristics: short-circuit current, open-circuit voltage, maximum power, and voltage at maximum power.

4.2 These parameters are derived by applying the procedure in Section 8 to a set of current-voltage data pairs (*I-V* data) recorded with the test module or array operating in the power-producing quadrant.

4.3 Testing the performance of a photovoltaic device involves the use of a calibrated photovoltaic reference cell to determine the total irradiance.

4.3.1 The reference cell is chosen according to the spectral distribution of the irradiance under which it was calibrated, for example, the direct normal or global spectrum. These spectra are defined by Tables G159G 173 . The reference cell therefore determines to which spectrum the test module or array performance is referred.

4.3.2 The reference cell must match the device under test such that the spectral mismatch parameter is 1.00 ± 0.05, as determined in accordance with Test Method E 973.

4.3.3 Recommended physical characteristics of reference cells are described in Specification E 1040.

4.4The spectral response of the module or array is usually taken to be that of a representative cell from the module or array tested in accordance with Test Method E1021

4.3.4 A reference module may be used instead of a reference cell throughout these test methods provided 4.3.2 is satisfied and the short-circuit current of the reference module has been determined according to the procedures in these test methods using a reference cell. The reference module must also meet the module package design requirements in Specification E 1040, with the exception of the electrical connector requirement. Ideally, electrical connections to an individual cell in the reference module should be provided to allow for spectral responsivity measurement according to Test Method E 1021.

4.4 The spectral response of the module or array is usually taken to be that of a representative cell from the module or array tested in accordance with Test Method E 1021. The representative cell should be packaged such that the optical properties of the module or array packaging and the representative cell package are similar.

4.5 The tests are performed using either natural or simulated sunlight. Solar simulation requirements are stated in Specification E 927.

4.5.1 If a pulsed solar simulator is used as a light source, the transient responses of the module or array and the reference cell must be compatible with the test equipment.

4.6 The data from the measurements are translated to a set of reporting conditions (see 5.3) selected by the user of these test methods. The actual test conditions, the test data (if available), and the translated data are then reported.

5. Significance and Use

5.1 It is the intent of these procedures to provide recognized methods for testing and reporting the electrical performance of photovoltaic modules and arrays.

5.2 The test results may be used for comparison of different modules or arrays among a group of similar items that might be encountered in testing a group of modules or arrays from a single source. They also may be used to compare diverse designs, such as products from different manufacturers. Repeated measurements of the same module or array may be used for the study of changes in device performance.

5.3 Measurements may be made over a range of test conditions. The measurement data are numerically translated ~~(see Section 8)~~ from the test conditions to ~~SRC,~~ standard RC, to nominal operating conditions, or to optional user-specified reporting conditions. ~~The SRC~~Recommended RC are defined in Table 1.

5.3.1 If the test conditions are such that the device temperature is within ±2°C of the RC temperature and the total irradiance is within ±5 % of the RC irradiance, the numerical translation consists of a correction to the measured device current based on the total irradiance during the *I-V* measurement.

5.3.2 If the provision in 5.3.1 is not met, performance at RC is obtained from four separate *I-V* measurements at temperature and irradiance conditions that bracket the desired RC using a bilinear interpolation method.[3]

5.3.2.1 There are a variety of methods that may be used to bracket the temperature and irradiance. One method involves cooling the module under test below the reference temperature and making repeated measurements of the *I-V* characteristics as the module warms up. The irradiance of pulsed light sources may be adjusted by using neutral density mesh filters of varying transmittance. If the distance between the simulator and the test plane can be varied then this adjustment can be used to change the irradiance. In natural sunlight, the irradiance will change with the time of day or if the solar incidence angle is adjusted.

5.4 These test methods are based on two requirements.

5.4.1 First, the reference cell (or module, see 1.1.1 and 4.3.4) is selected so that its spectral response is considered to be close to the module or array to be tested.

5.4.2 Second, the spectral response of a representative cell and the spectral distribution of the irradiance source must be known. The calibration constant of the reference cell is then corrected to account for the difference between the actual and the reference spectral irradiance distributions using the spectral mismatch parameter, which is defined in Test Method E 973.

5.5 Terrestrial reference cells are calibrated with respect to a reference spectral irradiance distribution, for example, Tables ~~G159~~G 173.

5.6 A reference cell made and calibrated as described in 4.3 will indicate the total irradiance incident on a module or array whose spectral response is close to that of the reference cell.

5.7 With the performance data determined in accordance with these test methods, it becomes possible to predict module or array performance from measurements under any test light source in terms of any reference spectral irradiance distribution.

~~[3] Burden, R. L., and Faires, J. D., *Numerical Analysis*, 3rd ed., Prindle, Weber & Schmidt, Boston, MA, 1985, p. 42 ff.~~

[3] Marion, B., Rummel, S., and Anderberg, A., "Current-Voltage Curve Translation by Bilinear Interpolation," Prog. Photovolt: Res. Appl. 2004, 12:593–607.

TABLE 1 Reporting Conditions

	Total Irradiance, Wm^{-2}	Spectral Irradiance	Device Temperature, ° C
~~Standard reporting conditions~~	~~1000~~	~~G 159~~	~~25~~
Standard reporting conditions	1000	G 173	25
Nominal operating conditions	800	...	NOCT

~~5.8These test methods are valid for the range of temperature and irradiance conditions over which the correction factors (defined in Annex A2) were determined. Devices for which the correction factors cannot be determined or are unavailable will have to be measured at temperature and irradiance conditions as close to the desired reporting conditions as possible.~~

5.8 The reference conditions of 5.3.1 must be met if the measured *I-V* curve exhibits "kinks" or multiple inflection points.

6. Apparatus

6.1 *Photovoltaic Reference Cell* —A calibrated reference cell is used to determine the total irradiance during the electrical performance measurement.

6.1.1 The reference cell shall be matched in its spectral response to a representative cell of the test module or array such that the spectral mismatch parameter as determined by Test Method E 973 is 1.00 ± 0.05.

6.1.2 Specification E 1040provides recommended physical characteristics of reference cells.

6.1.3 Reference cells may be calibrated in accordance with Test Methods E 1039, E 1125, or E 1362, as appropriate for a particular application.

6.1.4 A current measurement instrument (see 6.7) shall be used to determine the I_{sc} of the reference cell when illuminated with the light source (see 6.4).

6.2 *Test Fixture*— The device to be tested is mounted on a test fixture that facilitates temperature measurement and four-wire current-voltage measurements (Kelvin probe, see 6.3). The design of the test fixture shall prevent any increase or decrease of the device output due to reflections or shadowing. Arrays installed in the field shall be tested as installed. See 7.2.3 for additional restrictions and reporting requirements.

6.3 *Kelvin Probe*— An arrangement of contacts that consists of two pairs of wires attached to the two output terminals of the device under test. One pair of wires is used to conduct the current flowing through the device, and the other pair is used to measure the voltage across the device. A schematic diagram of an I-V measurement using a Kelvin Probe is given in Fig. 1 of Test Method E 948.

6.4 *Light Source*— The light source shall be either natural sunlight or a solar simulator providing Class A, B, or C simulation as specified in Specification E 927.

6.5 *Temperature Measurement Equipment* —The instrument or instruments used to measure the temperature of both the reference cell and the device under test shall have a resolution of at least 0.1°C, and shall have a total error of less than ±1°C of reading.

6.5.1 Temperature sensors, such as thermocouples or thermistors, suitable for the test temperature range shall be attached in a manner that allows measurement of the device temperature. Because module and array temperatures can vary ~~spacially~~spatially under continuous illumination, multiple sensors distributed over the device should be used, and the results averaged to obtain the device temperature.

6.5.2 When testing modules or arrays for which direct measurement of the cell temperature inside the package is not feasible, sensors can be attached to the rear side of the devices. The error due to temperature gradients will depend on the thermal characteristics of the packaging, especially under continuous illumination. Modules with glass back sheets will have higher gradients than modules with thin polymer backs, for example.

6.6 *Variable Load*— An electronic load, such as a variable resistor, a programmable power supply, or a capacitive sweep circuit, used to operate the device to be tested at different points along its *I-V* characteristic.

6.6.1 The variable load should be capable of operating the device to be tested at an *I-V* point where the voltage is within 1 % of V_{oc} in the power-producing quadrant.

6.6.2 The variable load should be capable of operating the device to be tested at an *I-V* point where the current is within 1 % of I_{sc} in the power-producing quadrant.

6.6.3 The variable load should allow the device output power (the product of device current and device voltage) to be varied in increments as small as 0.2 % of the maximum power.

6.6.4 The electrical response time of the variable load should be fast enough to sweep the required range of *I-V* operating points during the measurement period. It is possible that the response time of the device under test may limit how fast the range of *I-V* points can be swept, especially when pulsed simulators are used. For these cases, it may be necessary to make multiple measurements over smaller portions of the *I-V* curve to obtain the entire recommended range.

6.7 *Current Measurement Equipment* —The instrument or instruments used to measure the current through the device under test and the I_{sc} of the reference cell shall have a resolution of at least ~~0.02%~~0.05 % of the maximum current encountered, and shall have a total error of less than 0.1 % of the maximum current encountered.

6.8 *Voltage Measurement Equipment* —The instrument or instruments used to measure the voltage across the device under test shall have a resolution of at least ~~0.02%~~0.05 % of the maximum voltage encountered, and shall have a total error of less than 0.1 % of the maximum voltage encountered.

7. Procedures

7.1 *Momentary Illumination Technique* :

7.1.1 This technique is valid for use with pulsed solar simulators, shuttered continuous solar simulators, or shuttered sunlight. For testing under continuous illumination see 7.2.

7.1.2 Determine the spectral mismatch parameter, M, using Test Method E 973.

7.1.3 Mount the reference cell and the device to be tested in the test fixture coplanar within ±2°, and normal to the illumination source within ±10°. If an array or module cannot be aligned to within ±10°, the solar angle of incidence, the device orientation and its tilt angle must be reported with the data.

7.1.4 Connect the four-wire Kelvin probe to the module or array output terminals.

7.1.5 Expose the module or array to the light source.

7.1.6 If the temporal instability of the light source (as defined in Specification E 927) is less than 0.1 %, the total irradiance may be determined with the reference cell prior to the performance measurement. In this case, measure the short-circuit current of the reference cell, I_r.

7.1.7 Measure the *I-V* characteristic of the test device by changing the operating point with the variable load so that the provisions of 6.6 are met. At each operating point along the *I-V* characteristic, measure the device voltage, the device current, and I_r.

7.1.7.1 If the provision of 7.1.6 is met, it is not necessary to measure I_r at each operating point.

7.1.8 Measure the temperature of the reference cell, T_r, and the temperature of the test device, T_c. Temperature changes during the test shall be less than 2°C.

7.2 *Continuous Illumination Technique* :

7.2.1 This technique is valid for testing in continuous solar simulators or natural sunlight.

7.2.2 Determine the spectral mismatch parameter, M, using Test Method E 973.

7.2.3 Mount the reference cell and the device to be tested in the test fixture coplanar within ±2°, and normal to the illumination source within ±10°. If an array or module cannot be aligned to within ±10°, the solar angle of incidence, the device orientation and its tilt angle must be reported with the data.

7.2.4 Connect the four-wire Kelvin probe to the module or array output terminals.

7.2.5 Expose the test device to the illumination source for a period of time sufficient for the device to achieve thermal equilibrium.

7.2.6 If the temporal instability of the light source (as defined in Specification E 927) is less than 0.1 %, the total irradiance may be determined with the reference cell prior to the performance measurement. In this case, measure the short-circuit current of the reference cell, I_r.

7.2.7 Obtain the average temperature, T_c, of a cell in the module or array using one of the following two methods:

7.2.7.1 For outdoor measurements in natural sunlight if the NOCT correction factors are known (see Annex A1), measure the ambient air temperature and the wind speed. The average wind speed for 5 min preceding the test and during the test should not exceed 1.75 ms $^{-1}$.

7.2.7.2 Measure the temperature of the sensors, following the provisions of 6.5.

7.2.8 Measure the reference cell temperature, T_r.

7.2.9 Measure the *I-V* characteristic of the test device by changing the operating point with the variable load so that the provisions of 6.6 are met. At each operating point along the *I-V* characteristic, measure the device voltage, the device current, and I_r.

7.2.9.1 If the provision of 7.2.6 is met, it is not necessary to measure I_r at each operating point.

7.2.10 Immediately following the *I-V* recording, repeat the temperature measurements and verify that temperature changes during the test were less than 2°C.

7.3 If the provision of 5.3.1 is not met, repeat 7.1 or 7.2 three times to obtain a total of four *I-V* characteristics as required by 5.3.2.

8. Calculation of Results

8.1 Adjust the reference cell calibration constant using:

$$C' = \frac{C}{M}\,[1 + \alpha_r(T_r - T_o)] \qquad (1)$$

~~8.2Correct the current at each point of the *I-V* data for irradiance using the following equation:~~

$$I = I_m \frac{E_o C'}{I_r} \qquad (2)$$

~~where:~~

8.2 Calculate the total irradiance during the performance measurement(s) using the following equation (if I_m

~~= the uncorrected current as measured in Section 7.~~

~~8.3Calculate the total irradiance during the performance measurement using the following equation (if I_r~~ was measured at each operating point, use the average value of I_r): ~~E=~~

$$E = \frac{I_r}{C'} \qquad \text{~~(2)~~}$$

~~8.4Determine the uncorrected short-circuit current,~~

8.3 If the provision in 5.3.1 is met, correct the current at each point of the *I-V* data for irradiance using the following equation:

$$I = I_m \frac{E_o}{E} \tag{3}$$

8.4 If the provision in 5.3 is not met, use the bilinear interpolation method specified in 5.3.2 to calculate the *I-V* characteristic at RC using the four *I-V* curves obtained in 7.3.

8.5 Determine the short-circuit current, ~~I_{scu}~~I_{sc}, from the *I-V* data using one of the following procedures:

~~8.4.1~~

8.5.1 If an *I-V* data pair exists where V is 0.0 ± 0.005 V_{oc}, I from this pair may be considered to be the short-circuit current.

~~8.4.2If the condition in 8.4.1~~

8.5.2 If the condition in 8.5.1 is not met, calculate the short-circuit current from several *I-V* data pairs where V is closest to zero using linear interpolation or extrapolation.

~~8.5Determine the uncorrected open-circuit voltage,~~

8.6 Determine the open-circuit voltage, ~~V_{ocu}~~V_{oc}, from the *I-V* data measured in Section 7 using one of the following procedures:

~~8.5.1~~

8.6.1 If an *I-V* data pair exists where I is 0.0 ± 0.001 I_{sc}, V from this pair may be considered to be the open-circuit voltage.

~~8.5.2If the condition in 8.5.1~~

8.6.2 If the condition in 8.6.1 is not met, calculate the open-circuit voltage from several *I-V* data pairs where I is closest to zero using linear interpolation or extrapolation.

~~8.6Translate the uncorrected short-circuit current to RC using the following equation:~~

$$I_{sc} = \frac{I_{scu}}{[1+\alpha(T_c - T_o)]} \tag{4}$$

~~8.7Translate the uncorrected open-circuit voltage to RC using the following equation:~~

$$V_{oc} = \frac{V_{ocu}}{[1+\beta(E_o)(T_c - T_o)][1+\delta(T_c)\ln(E/(E_o)]} \tag{5}$$

~~NOTE1—The translation functions α, β, and δ are obtained from experimental determination. An acceptable method is described in Annex A2. Measurement of the translation functions for every device tested is not required; functions previously determined for a device of identical design and construction may be used.~~

~~8.8Translate each~~

8.7 If the provision in 5.3.1 is not met, use the bilinear interpolation method specified in 5.3.2 to calculate the *I-V* ~~data point to RC using the following equations:~~

$$I_o = I \frac{I_{sc}}{I_{scu}} \tag{6}$$

~~and:~~

$$V_o = V \frac{V_{oc}}{V_{ocu}} \tag{7}$$

~~8.9Form a table of~~ *characteristic at RC.*

8.8 Form a table of P versus V_o values by multiplying I_o by V_o.

~~8.10Find~~8.9 Find the maximum power point P_m, and the corresponding V_{mp}, in the P versus V_o table. Because of random fluctuations and the probability that one point in the tabular I_o-V_o data will not be exactly on the maximum power point, it is recommended that the following procedure be used to calculate the maximum power point, especially for devices with fill factors greater than 80 %.

~~8.10.1~~

8.9.1 Perform a fourth-order polynomial least-squares fit to the P versus V_o data that are within the following limits:

$$0.751_{mp} \leq I_o \leq 1.15 I_{mp} \tag{4}$$

and:

$$0.75 V_{mp} \leq V_o \leq 1.15 V_{mp} \tag{5}$$

These limits are guidelines that have been found to be useful for this procedure and need not be followed precisely. This results in a polynomial representation of P as a function of V_o.

~~8.10.1.1It~~8.9.1.1 It is recommended that a plot of the I_o-V_o data and the polynomial fit be made to visually assess the reliability of the fit.

~~8.10.1.2Fewer~~8.9.1.2 Fewer data points used for the polynomial fit may require the polynomial order to be reduced.

~~8.10.2~~8.9.2 Calculate the derivative polynomial of the polynomial obtained from ~~8.10.1~~8.9.1.

~~8.10.3Find~~8.9.3 Find a root of the derivative polynomial obtained from ~~8.10.2~~8.9.2 using V_{mp} as an initial guess. An appropriate