Designation: E2527 – 15

Standard Test Method for Electrical Performance of Concentrator Terrestrial Photovoltaic Modules and Systems Under Natural Sunlight[1]

1. Scope

1.1 This test method covers the determination of the electrical performance of photovoltaic concentrator modules and systems under natural sunlight using a normal incidence pyrheliometer.

1.2 The test method is limited to module assemblies and systems where the geometric concentration ratio specified by the manufacturer is greater than 5.

1.3 This test method applies to concentrators that use passive cooling where the cell temperature is related to the air temperature.

1.4 Measurements under a variety of conditions are allowed; results are reported under a select set of concentrator reporting conditions to facilitate comparison of results.

1.5 This test method applies only to concentrator terrestrial modules and systems.

1.6 This test method assumes that the module or system electrical performance characteristics do not change during the period of test.

1.7 The performance rating determined by this test method applies only at the period of the test, and implies no past or future performance level.

1.8 *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]

D6176 Practice for Measuring Surface Atmospheric Temperature with Electrical Resistance Temperature Sensors

E772 Terminology of Solar Energy Conversion

E816 Test Method for Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers

E1036 Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells

2.2 *IEEE Standard:*

IEEE 929-2000 Recommended Practice for Utility Interface of Photovoltaic (PV) Power Systems

3. Terminology

3.1 *Definitions*—Definitions of terms used in this test method may be found in Terminology E772, and IEEE Standard 929.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *Concentrator Reporting Conditions, n*— the ambient temperature, wind speed, and direct normal solar irradiance to which concentrator module or system performance data are corrected..

3.2.2 *system, n*—a photovoltaic module or array connected to an inverter.

3.3 *Symbols:*The following symbols and units are used in this test method:

E = direct normal irradiance, Wm^{-2}
E_o = reporting direct normal irradiance of 850 Wm^{-2}
P = maximum power, W
P_o = maximum power at concentrator reporting conditions (E_o, T_o, and V_o), W
T_a = ambient temperature, °C
T_o = reporting ambient temperature of 20°C
v = wind speed, ms^{-1}
v_o = reporting wind speed of 4 ms^{-1}

4. Summary of Test Method

4.1 Determining the performance of a photovoltaic module or system under natural sunlight consists of measuring the maximum power over a range of irradiance and air temperature.

[1] This test method is under the jurisdiction of ASTM Committee E44 on Solar, Geothermal and Other Alternative Energy Sources and is 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.

4.2 A multiple linear regression is used to rate the maximum power[3] at standard concentrator reporting conditions, defined as T_o = 20°C, v_o = 4 ms^{-1}, E_o = 850 Wm^{-2}.

4.2.1 A direct normal irradiance of 850 Wm^{-2} was selected from a resource assessment study[4] that showed when the global normal solar irradiance is near the 1000 Wm^{-2} used in rating flat-plate photovoltaic modules, the direct normal irradiance is about 850 Wm^{-2}.

4.3 The actual test data and the performance results are then reported.

5. Significance and Use

5.1 It is the intent of this test method to provide a recognized procedure for testing and reporting the electrical performance of a photovoltaic concentrator module or system.

5.2 If an inverter is used as part of the system, this test method can provide a dc or ac rating or both. The dc or ac rating depends on whether the inverter input or output is monitored.

5.3 The test results may be used for comparison among a group of modules or systems 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 system may be used for the study of changes in device performance over a long period of time or as a result of stress testing.

5.4 The test method is limited to modules and systems where the concentrated irradiance on the component cells is greater than 5000 Wm^{-2} at E_o. This limitation is necessary because the total irradiance is measured with a radiometer with a field of view less than 6° and because the correlation between the direct irradiance and the power produced decreases with increasing concentrator field of view.

5.5 This test method assumes that the regression equation accurately predicts the concentrator performance as a function of total irradiance with a fixed spectral irradiance, wind speed, and air temperature. The spectral distribution will be seasonal and site specific because of optical air mass, water vapor, aerosols, and other meteorological variables.

6. Apparatus

6.1 *Test Fixture*—A platform that maintains an incidence angle to the sun of less than 0.5°. If the manufacturer's specifications require more accurate tracking than 0.5° incidence angle, the manufacturer's specifications should be followed. Concentrator systems shall be tested as installed.

6.2 *Air Temperature Measurement Equipment*—The instrument or instruments used to measure the temperature of the air shall have a resolution of at least 0.1°C, and shall have a total error of less than ±1°C of reading. The instrument sensor should be between 1 and 10 m upwind from the geometrical center of the receiver and be mounted at least 2 m above the ground. Further details on air temperature measurements can be found in Practice D6176.

6.3 *Irradiance Measurement Equipment*—A secondary reference pyrheliometer calibrated according to Test Method E816.

6.4 *Wind Speed Measurement Equipment*—The instrument used to measure the wind speed should have an uncertainty of less than 0.5 ms^{-1}. The instrument should be between 1 and 10 m away from the nearest edge of the receiver and be mounted at least 2 m above the ground. Ideally, the instrument should be at the center height of the receiver and located in the direction of the prevailing wind. Care should be taken that the instrument readings are not affected by the test fixture or nearby obstacles.

6.5 *Power Measurement Equipment*—Examples of acceptable instrumentation to measure the output power of the module or system under test include:

6.5.1 Current-voltage measurement instrumentation required by Test Methods E1036,

6.5.2 ac or dc current and voltage measurement instrumentation, and

6.5.3 ac or dc power meter.

7. Procedure

7.1 If required, mount the module or system to be rated on the tracking platform..

7.2 Connect the module or system to be rated to the power measurement equipment.

7.3 Measure the direct solar irradiance E, air temperature T_a, and the wind speed v.

7.4 Measure the maximum power according to 7.2.9 of Test Methods E1036. If an inverter is part of the system, measure the ac or dc output power of the system.

7.5 Ensure the maximum interval between data points is 5 min.

7.6 Reject data when the direct normal solar irradiance is less than 750 W m^{-2}, the irradiance varies by more than 10 % from the maximum value to the minimum value recorded during any 10 min interval, or the wind speed is greater than 8 m s^{-1}. If the wind speed exceeds 15 m s^{-1}, reject all data during the succeeding 10 min interval.

7.7 Repeat 7.3 through 7.6 until at least 20 valid points are obtained. For best results the data points should be distributed around the standard concentrator reporting conditions (T_o, v_o, and E_o).

8. Calculation of Results

8.1 Compute the regression coefficients a_1, a_2, a_3, a_4 by performing a multiple linear regression of P as a function of E, v, and T_a using: [5]

[3] Hester, S. I., Townsend, W. T., Clements, W. T., and Stolte, W. J., "PVUSA Lessons Learned from Startup and Early Operation," Proc. of the 21st IEEE Photovoltaics Spec. Conf., IEEE, New York, NY, 1990, pp. 937-943.

[4] Kurtz, S., Myers, D., Townsend, T., Whitaker, C., Maish, A., Hulstrom, R., and Emery, K., "Outdoor Rating Conditions for Photovoltaic Modules and Systems," *Solar Energy Mater. Solar Cells* 62, 2000, pp. 379-391.

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

$$P = E(a_1 + a_2 \cdot E + a_3 \cdot T_a + a_4 \cdot v) \quad (1)$$

8.2 Calculate the maximum power at the concentrator reporting conditions:

$$P_o = E_o(a_1 + a_2 \cdot E_o + a_3 \cdot T_o + a_4 \cdot v_o) \quad (2)$$

8.3 If the standard error of estimate for P_o is greater than 3 % repeat 7.3 through 7.5.

9. Report

9.1 The end user ultimately determines the amount of information to be reported. Listed below are the minimum, mandatory reporting requirements:

9.2 *Concentrator Test Module or System Description:*

9.2.1 Identification,

9.2.2 Physical description, and

9.2.3 Aperture area.

9.3 *Radiometer Description:*

9.3.1 Identification,

9.3.2 Physical description,

9.3.3 Calibration laboratory,

9.3.4 Calibration procedure,

9.3.5 Date of calibration, and

9.3.6 Calibration constant.

9.4 Description of power measurement equipment and method.

9.5 *Test Conditions:*

9.5.1 Geographical location, and

9.5.2 Date and time of tests.

9.6 *Test Results:*

9.6.1 Table of P, E, v, T_a used in the regression or graph of the data and fit,

9.6.2 Number of days, and number of points used in the regression analysis, and

9.6.3 Regression coefficients and standard error of estimate.

9.6.4 If range of T_o does not encompass the reported ambient temperature, T_o, then the report should include a note that the reporting data is extrapolated and the maximum and minimum of T_o should be reported.

10. Precision and Bias

10.1 *Precision*—It is not practicable to specify the precision of the concentrator performance rating using results of an interlaboratory study, because the results are site and time specific (see 5.5) and such a study would require circulating at least six stable concentrator modules and associated tracking hardware between all participating laboratories. Factors that contribute to the total precision include:

10.1.1 Temporal variations of the solar spectrum and total irradiance during the measurement of the total irradiance and maximum power.

10.1.2 Variation of the direct normal spectral irradiance from data point-to-data point will introduce an error because the data is not being referenced to a fixed reference spectral irradiance distribution.

10.1.3 Temperature variations in the device under test not correlated with E, v, and T_a. This may arise from the finite mass of the concentrator assembly or thermal gradients between the cell junction temperature and the rest of the concentrator.

10.1.4 Electronic instrumentation used to measure the output power.

10.2 The contribution of bias to the total error will depend upon the bias of each individual parameter used for the determination of P, E, v, and T_a.

10.2.1 The location of the temperature sensor used to measure T_a with respect to the concentrator will appear as a bias error.

10.2.2 An absolute accuracy of 0.45 % for terrestrial radiometric measurements has been established for absolute cavity radiometers that have been compared with the World Radiometric reference. If a secondary reference pyrheliometer is used, a 1% transfer error from the cavity radiometer should be expected when utilizing procedures of Test Method E816.

10.2.3 Misalignment between the sun and concentrator module will introduce a bias error that will depend on the concentration ratio.

11. Keywords

11.1 concentrator; modules; performance; photovoltaic; rating; reporting; systems; testing