Considerations for How to Rate CPV

Sarah Kurtz, Matthew Muller, Bill Marion, and Keith Emery
National Renewable Energy Laboratory

Robert McConnell
Amonix, Inc.

Sandheep Surendran
Surya Design

Adrianne Kimber
First Solar, Inc.

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Sarah Kurtz[1], Matthew Muller[1], Bill Marion[1], Keith Emery[1], Robert McConnell[2], Sandheep Surendran[3], Adrianne Kimber[4]

[1]National Renewable Energy Laboratory, Golden, CO, 80401 USA
[2]Amonix, Inc, 3425 Fujita Street, Torrance, CA 90505 USA
[3]Surya Design, 290 Division St. Suite 401, San Francisco, CA 94110 USA
[4]First Solar Inc., 1111 Broadway, 4th Floor, Oakland, CA 94706 USA

Abstract: The concentrator photovoltaic (CPV) industry is introducing multiple products into the marketplace, but, as yet, the community has not embraced a unified method for assessing a nameplate rating. The choices of whether to use 850, 900, or 1000 W/m^2 for the direct-normal irradiance and whether to link the rating to ambient or cell temperature will affect how CPV modules are rated and compared with other technologies. This paper explores the qualitative and quantitative ramifications of these choices using data from two multi-junction CPV modules and two flat-plate modules.

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INTRODUCTION

The CPV industry currently uses a variety of conditions for determining the module nameplate rating, thus reflecting a lack of consensus. Current web-published datasheets for nine high-concentration PV (HCPV) products show that four use 850 W/m^2, three use 1000 W/m^2, one uses 900 W/m^2, and one did not specify the irradiance for the power rating. For the same set of datasheets, one used 20°C ambient, two used 25°C ambient, two used 25°C cell, and four were unclear about the temperature used for the rating. The inconsistency in definition of nameplate rating causes confusion, and industry leaders agree that the adoption of a single international standard for power rating is a priority for the CPV community, but there is substantial controversy over which conditions and methodology should be used. Careful choice of ratings can facilitate acceptance of CPV; poor choices may lead to confusion and create barriers.

This paper identifies types of ratings, how they may be used, and criteria for selecting amongst them. Past precedents and new proposals for the rating conditions and methodology are summarized. The ramifications of these choices are reviewed and conclusions drawn from these.

OBJECTIVES OF RATINGS

A power rating is recorded on the module nameplate and may be used as the basis of incentives, for describing the size of installations, for verification of system delivery, and for sizing of inverters and other system parts. An energy rating depends on the available sunshine and helps to assess the expected return on investment, providing a key input for calculating the cost of the electricity. These objectives are summarized in Tables 1 and 2, respectively. The power rating is usually applied at the module level; estimation of energy production is most relevant at the system level. For CPV, variability in alignment of a module and the quality of the tracker may affect the rating.

Depending on which objective is being considered, the best choice of rating method could change. Table 3 summarizes some of the criteria that may be considered when choosing a rating methodology and conditions.

DETAILS OF POWER RATING

Power Rating Conditions

Rating conditions that have been used historically or that have been suggested for current consideration are summarized in Table 4. The survey of CPV datasheets described above showed that there is no consensus about which of these to use. The two conditions that have stimulated the strongest debate are the irradiance and temperature. If outdoor rating is used, wind speed and direction, spectral variations, and tracker misalignment also need to be addressed, but space limitations prevent careful treatment of these here.

TABLE 1. Objectives for Power Rating.

Objective	Comment
Provide basis for per-watt incentives	Whereas per-watt incentives have been used for small flat-plate systems, CPV incentives may be tied to energy production.
Nameplate rating (compare products; verify delivery of product)	CPV rating is based on direct irradiance instead of global irradiance, complicating the comparison between CPV and flat-plate nameplate ratings.
Provide metric for counting production volume, etc.	Rating at 850 W/m^2 rather than 1000 W/m^2 would count 15% less W installed in the field.
Define peak output for sizing components	The peak output depends on the location.
Provide starting point for energy rating	The translation from power to energy has been quite successful for flat-plate silicon. For thin-film and CPV, this conversion is less known.
Provide metric for quality assurance during manufacturing	Manufacturers need to ensure performance of product, but may use a more cost-effective process than the rating methodology.

TABLE 2. Objectives for Energy Rating.

Objective	Comment
Provide basis for return on investment calculations to satisfy investors	Investors are currently cautious, especially for investment in new technologies. To provide high confidence, the rating method should be comparable to flat-plate energy rating.
Provide basis for estimating the cost of solar electricity	Can drive R&D choices.
Provide basis for per kWh incentives	Incentives may be based on what is measured rather than what is rated.
Provide metric for ongoing assessment of system health	This metric could differ from what is given to the investor.

TABLE 3. Criteria for Judging Rating Methodologies.

Criterion
Cost (ease) of completing rating
Time to complete rating
Accuracy (reproducibility) of rating
Ease of comparison with flat plate
Simplicity (number of assumptions)
Applicability to all CPV designs
Executability (measurability) at any location/lab

TABLE 4. Currently Used or Proposed Module Power Rating Conditions.

Source	Description
Flat plate precedent: IEC 61215 Standard test conditions (STC)[2]	1000 W/m^2 global*; 25°cell.
Flat plate precedent: IEC 61215 Nominal operating cell temperature (NOCT)[2]	800 W/m^2 global*; 20°C ambient; 1 m/s wind speed.
CPV precedent: IEC 62108 default conditions[3]	900 W/m^2 direct; 25°C cell; 3 m/s wind speed
CPV precedent: PVUSA,[4] ASTM E2527[5]	850 W/m^2 direct; 20°C ambient; prevailing spectrum; 1 or 4 m/s wind speed.
CPV precedent: Progress in PV efficiency tables [6]	1000 W/m^2 defined as one sun; 25°C cell; ASTM G173 direct spectrum.
CPV proposed: Concentrator Standard Nominal Condition[7]	850 W/m^2 direct; 20°C ambient; 2 m/s wind speed.
CPV proposed: High Irradiance Condition[7]	1000 W/m^2 direct; 20°C ambient; 2 m/s wind speed.
CPV proposed: High Temperature Condition[7]	850 W/m^2 direct; 40°C ambient; 2 m/s wind speed.
CPV proposed: Integrate ASTM G173 spectrum	900 W/m^2 direct.

* IEC 60904-3, similar to ASTM G173 global spectrum, defines the global spectrum for the IEC measurements.

Irradiance for Power Rating

Three values of irradiance (850, 900, and 1000 W/m^2) are being used to rate CPV modules today. The arguments for using each of these are summarized in Table 5. One study[1] of more than 30 sites correlated global normal irradiance (GNI) between 975 and 1025 W/m^2 with DNI between 789 and 875 W/m^2, implying that 850 W/m^2 is the best of the proposed DNI values. However, many of the best sites for CPV routinely experience GNI higher than the 975-1025 W/m^2 condition used in the study, and, thus, may not accurately reflect prevailing conditions. To quantify the importance of the methodology for determining the DNI to GNI ratio, we investigated DNI/GNI data measured in Golden, CO for the year 2008. Hourly data (including cloudy days) were divided into 50 W/m^2 bins (Fig. 1), finding an average DNI to average GNI ratio of 0.780 for 975 W/m^2 < GNI <1025 W/m^2 and a ratio of 0.83 if GNI > 975 W/m^2 is considered. Thus, for this set of data, including the higher GNI data increases the suggested DNI value by 50 W/m^2. This difference is substantial, indicating the need for a new study.

TABLE 5. Arguments for Irradiance Condition Choices

Direct Normal Irradiance	Arguments for
1000 W/m^2	Often defined as "one sun".
900 W/m^2	Accounts for reduced irradiance in the direct beam for locations with clearest skies; ASTM G173 direct spectrum integrates to 900 W/m^2.
850 W/m^2	Accounts for reduced irradiance in direct beam[8]; consistent with PVUSA[4] and ASTM E2527[5].

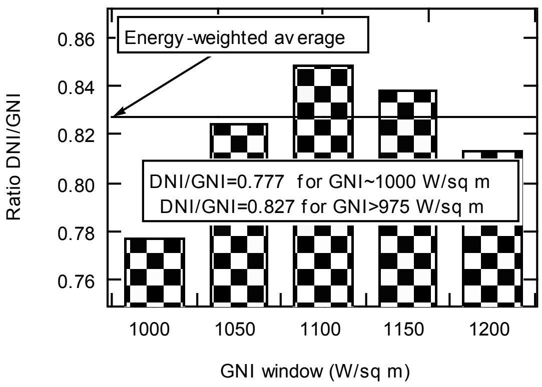

FIGURE 1. Ratio of DNI to GNI as a function of the GNI, sorted into ±25 W/m^2 bins for Golden, CO in 2008.

It is appropriate for a module to generate its rated power under peak conditions. The fraction of time for which the rated power was exceeded for CPV and flat-plate modules in Golden, CO is compared in Fig. 2.

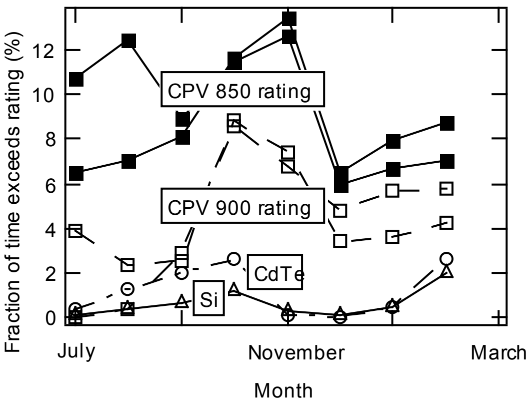

FIGURE 2. Fraction of time, including nighttime, for which the rated power was exceeded for two CPV and two flat-plate modules in Golden, CO. Maximum-power-point data were derived from current-voltage curves measured for individual modules in 2009-2010. The CPV rating used 20°C ambient and either 850 or 900 W/m^2 irradiance. The flat-plate ratings used 25°C and 1000 W/m^2 irradiance. The CPV modules were mounted on a 2-axis tracker; the flat-plate modules were mounted at a fixed latitude tilt.

Temperature for Power Rating

The effect of the choice of using 25°C module (cell) temperature versus 20°C ambient temperature is shown in Fig. 3. Under full sun, PV modules typically operate ~25-60°C hotter than ambient.[9] Assuming ~30°C temperature shift, a module is expected to operate at ~50°C when the ambient temperature is 20°C, generating 6%-12% less than its nameplate rating if it was rated at 25°C cell temperature, as shown by the lower set of curves in Fig. 3. This discrepancy between nameplate power and actual power in the field is avoided when the rating is determined relative to ambient temperature, as shown in the upper curve in Fig. 3. CPV modules are likely to operate with cell temperatures more than 30°C above ambient,[9] which would cause the lower set of curves in Fig. 3 to shift to the left if a CPV module were rated at 25°C cell temperature. Thus, a CPV module rated at 25°C cell temperature would operate ~6%-15% lower in the field compared to one rated using 20°C ambient temperature. The two methods are compared in Table 6. If 20°C ambient is used as the rating condition, then indoor measurements would require inconvenient heating of the module to the cell operating temperature.

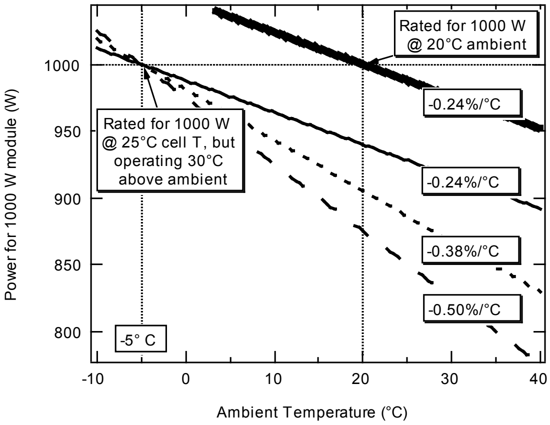

FIGURE 3. Effect of rating modules at 20°C ambient or 25°C cell temperature on expected in-field performance, assuming operation at 30°C above ambient. The topmost curve indicates performance under the rated irradiance condition for a module rated at 20°C ambient with a temperature coefficient of -0.24%/°C. The lower curves represent modules operating 30°C above ambient with three different temperature coefficients. Most silicon modules have temperature coefficients between -0.50%/°C and -0.38%/°C. Thin-film modules often show smaller temperature effects; CPV cells typically have temperature coefficients of ~ -0.2%/°C.

TABLE 6. Comparison of Advantages for Choice of Temperature Condition.

Ambient @ 20°C	**Cell @ 25°C**
Modules operate closer to rated power	Consistent with flat plate.
Modules with good thermal management receive a higher rating, consistent with expected performance	Convenient for indoor measurement.
Avoid question of how to define/measure cell temperature	

Power Rating Method

Indoor Versus Outdoor Power Rating

The power rating for flat-plate modules may be determined either indoors or outdoors, though the methods for the measurements are somewhat different. Solar simulators emit light with an angular distribution different from that of sunlight. CPV optics are optimized for typical solar angular distribution; use of an indoor simulator can significantly change the measured power because the intensity and distribution of light reaching the cells is a function of the angular distribution of the light. Table 7 compares indoor and outdoor measurements of CPV. For the "Combined" measurement, an outdoor measurement calibrates the indoor measurement by defining the irradiance needed from the simulator to duplicate the photocurrent measured outdoors.

Methodologies for Outdoor Power Rating

A number of methods have been proposed for determining a power rating outdoors. These are summarized in Table 8.

TABLE 7. Indoor Versus Outdoor Measurements.

Method	Advantage	Disadvantage
Outdoor	• Collimation of light is "correct" though variable • Cell at operating temperature.	• Dependent on weather • Inconvenient • Cell temperature may not be known.
Indoor	• Repeatable • Reliable (independent of weather) • Cell temperature is known.	• Collimation may not be correct, giving incorrect intensity and distribution of light • Cell not at operating temperature.
Combined	• Accuracy of outdoor measurement with convenience of indoor.	• Temperature distribution within module is not realistic, potentially affecting alignment.

IMPACT OF POWER RATING DETAILS ON METRICS

Common metrics used to compare PV performance include yield, performance ratio, and mean efficiency. IEC 61724 defines how to measure and calculate most system parameters.[10] The performance ratio is given by:

$$R_P = \frac{electricity(kWh/day)\big/installed(kW)}{irradiance(kWh/day)\big/irradiance_{reference}(kW)}.$$

The performance ratio is insensitive to the irradiance reference condition, but decreases if a 25°C cell temperature is used for rating the modules instead of 20°C ambient temperature.

Fig. 4 compares the performance ratio measured for multiple HCPV and flat-plate modules during the last year. The CPV performance ratios were calculated relative to a PVUSA rating (derived at 20°C ambient temperature and 850 W/m^2 irradiance); the flat-plate ratings were based on simulator measurements at 25°C module temperature and 1000 W/ m^2 irradiance. Based on an assumed cell temperature 40°C above ambient and an assumed temperature coefficient of -0.24%/°C for the HCPV modules, we expect that CPV performance ratios would drop about 10% if a 25°C cell temperature were chosen for the power rating condition. Thus, if 20°C ambient temperature is used for rating the CPV modules, their performance ratios in Golden, CO will typically be greater than those

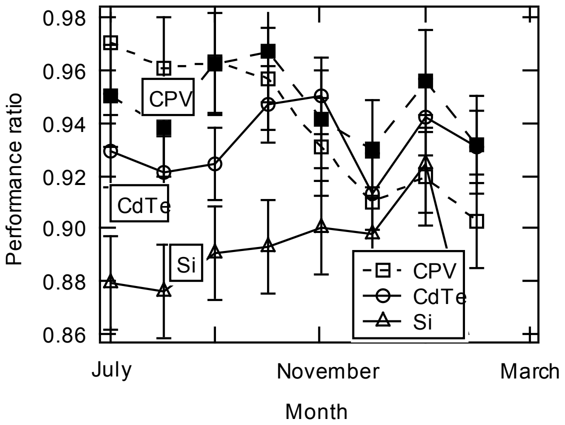

FIGURE 4. Performance ratio comparison for same dataset as shown in Fig. 2. If installed in complete systems, the CPV system performance may decrease more than the flat-plate.

TABLE 8. Currently Proposed Methods for Outdoor Power Rating.

Method	Features	Advantages	Challenges
PVUSA[4]; ASTM E2527[5]	Use days or weeks worth of data with linear regression relative to ambient temperature, DNI, wind speed.	Directly related to field performance.	Can take weeks; Some locations may not experience weather conditions similar to the requested test conditions.
ISFOC[11]	Use diode model to translate measurements to 850 W/m^2 and 60°C cell temperature.	Only one (clear) day's data is needed.	Need to define how to measure cell temperature; Model parameters may be unknown.
CPV version of IEC 61853 Pt 1–outdoor[7]	Quantifies performance under a variety of conditions.	Consistent with flat-plate approach.	May not be feasible to adjust the temperature and irradiance for a CPV module using filters, etc.

observed for flat-plate in the summer and (usually) in the winter. If the CPV ratings used 25°C cell temperature, the flat-plate modules would likely show higher performance ratios than the CPV modules. The comparison is dependent on location/weather.

DISCUSSION/CONCLUSIONS

As the CPV industry matures, a growing number of companies are using simulators to routinely characterize modules, implying a need for standard procedures to characterize CPV modules both indoors and outdoors. The method for indoor measurements is not well established, but may entail adjusting the simulator intensity based on an outdoor measurement of the photocurrent generated by a reference module. In order to facilitate both indoor and outdoor measurements, we recommend adopting standards for both "test" and "operating" conditions. The STC and NOCT conditions described in Table 4 for flat-plate measurements were designed for the convenience of testing (STC) and to reflect the higher temperatures expected during operation (NOCT). It is convenient and appropriate that indoor tests characterize performance at 25°C cell temperature, while 20°C ambient be used to characterize operating conditions. The use of 25°C cell temperature for CPV standard "test" conditions would be consistent with flat-plate and the Progress in PV[6] convention. Implementation of this recommendation outdoors will require development of a procedure to define the cell temperature for all types of CPV modules.

The choice of irradiance condition is complicated by the variability in conditions around the world. We recommend use of 900 W/m^2 for the irradiance condition to be consistent with the integrated direct-beam reference spectrum, which was designed to reflect optimal CPV conditions. The 900 W/m^2 value was also noted as the default in IEC 62108.[3] The study[1] that concluded that 850 W/m^2 is the better value neglected high GNI data, causing a systematic bias. There is some benefit in using the same irradiance for both the test and operating conditions, but use of 850 W/m^2 may be considered to characterize operating conditions to be consistent with historical measurements. If the community wishes to create a standard relevant to less-optimal CPV conditions, then 850 W/m^2 would be the better choice.

For characterization at standard operating conditions, it will be necessary to define the wind speed. We note that the use of wind speed averaged over 1-5 min before the measurement may be more useful than the instantaneous wind speed. The wind direction can also be important in determining the module temperature, but may be difficult to include as part of a rating standard.

Modules using multijunction solar cells can be sensitive to spectral variations. Defining the spectral condition by placing limits on the air mass or by explicitly measuring the spectrum will improve the reproducibility of the rating.

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13. **SUPPLEMENTARY NOTES**

14. **ABSTRACT** *(Maximum 200 Words)*

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