Minimizing Variation in Outdoor CPV Power Ratings

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Abstract. The CPV community has agreed to have both indoor and outdoor module power ratings. The indoor rating provides a repeatable measurement off the factory line while the outdoor rating provides a measure of true on-sun performance. The challenge with an outdoor rating is that conditions that impact the measurement such as the spectrum, temperature, wind speed, etc are constantly in flux. This work examines methodologies for determining the outdoor power rating with the goal of minimizing variation even if data are collected under changing meteorological conditions.

Keywords: CPV, Power Rating, Spectrum, IEC standards
PACS: 80,88

INTRODUCTION

The CPV community has been working to standardize a procedure for rating module power. According to the most recent IEC TC82 WG7 agreement, there will be an indoor power rating at concentrator standard test conditions (CSTC, 25C cell, 1000W/m^2) and an outdoor power rating at concentrator standard operating conditions (CSOC, 20C ambient, 900W/m^2). [1]. While the development of both these procedures present significant challenges, this paper focuses on the outdoor power rating.

NREL has been accumulating outdoor performance data on CPV modules from various manufacturers since early 2009. This paper examines this data set as a means to minimize variation of CPV module power ratings under CSOC. Specifically the following questions are addressed:

1) If a given module is measured over multiple months, with bounds placed on tracking accuracy, ambient temperature, wind conditions, 500 nm Aerosol Optical Depth (AOD), Precipitable Water Vapor (PWV), and geometric AirMass (AM), how consistent will the power measurement be?

2) For a given module, How consistent of a power rating can be achieved when applying a statistical regression to monthly data sets?

3) Is there an alternative to statistical regression that results in monthly power ratings with less variation?

OUTDOOR MEASUREMENT CHALLENGES

It is difficult to rate module power under outdoor conditions and achieve consistent results. Flat-plate PV uses indoor simulators specifically to avoid this problem but the unique designs of CPV present a need to use on-sun measurements. It is a useful starting point to understand how much power varies under clear-sky conditions for both tracked flat-plate and CPV. In efforts to restrict data to clear-sky CSOC conditions, a baseline filter has been applied to the data used throughout this work. Specifically, the following is accepted:

Direct Normal Irradiation (DNI) ≥750 W/m^2
Diffuse Irradiation ≤140 W/m^2
10C ≤Ambient Temperature ≤30C
5 minute DNI deviation ≤2%
Tracking Error ≤0.15 degrees
Instantaneous Wind Speed ≤5m/s
5 minute average Wind Speed ≤5m/s

The basis of the above filtering comes from ASTM E 2527-06 [2] with the restrictions on diffuse radiation and DNI deviation created to ensure no clouds or haze are within 10 degrees of the sun. Tracking error criteria were added as an extra precaution to reject data when the tracker is off-sun for any reason and to remove any relationship with tracking that might be seen for modules with tight acceptance angles.

Figure 1 shows July through December power data for both a tracked flat-plate module and a CPV module. The flat-plate data cover a greater irradiance range as they are measured against global normal irradiance (GNI) rather than DNI. Measured Power is divided by a rated power at 900 W/m^2 so both modules can be easily compared on the same graph.

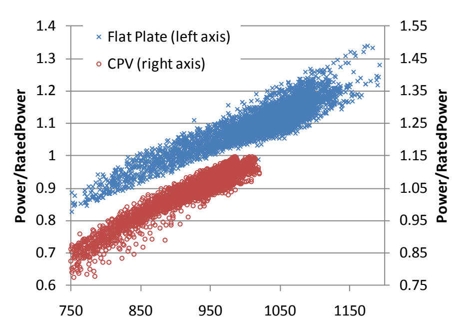

Fig. 1 Power Variation for Flat-Plate and CPV

The left and right axes have been intentionally shifted so the data do not fall on top of each other. While both modules show power variations of at least 10% at various irradiances, the flat-plate, in general, shows slightly higher variation than the CPV. Figure 2 presents the same data set as Fig. 1 but all data points have been corrected to a cell temperature that is representative of each module at CSOC.

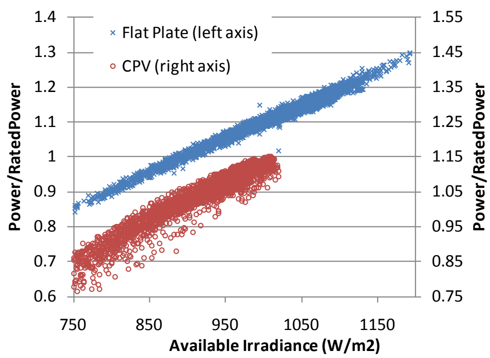

Fig.2 Temperature Corrected Flat-plate and CPV Data

It is clear that the temperature correction significantly reduces variation for the flat-plate module but the changes are subtle for the CPV module. The CPV module shows an increase in data scatter at low DNI, a slight tightening at high DNI, and a bend that becomes more noticeable around 850 W/m^2. It is not that the temperature correction has failed for the CPV module, but rather significant variation remains due to spectral effects. Because of the 10% variation still seen after a temperature correction it is logical to consider filtering or putting bounds on various parameters that impact CPV performance. Figure 3 is the temperature corrected data with additional filtering such that PWV is between 1-3 cm, and AOD is between 0.06 and 0.135. Comparing Fig.2 to Fig.3, the variation in power for a given DNI is reduced by almost half.

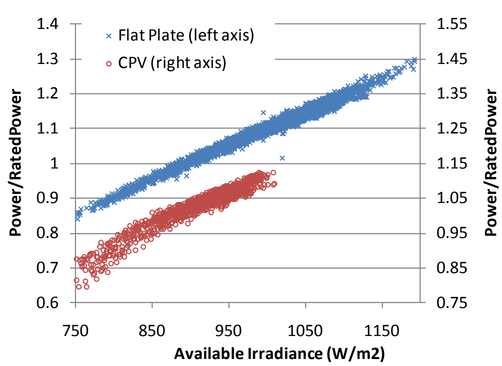

Fig.3 CPV Power Data with Spectral Filtering

The improvements seen in Fig.3 are primarily due to PWV filtering while AOD filtering added only slight benefits. Additional filtering was applied to limit AM and the results were that high and low DNI data were removed but that variation for mid-range DNI was unchanged. Removing data with AM greater than 2 does prove useful to eliminate data with increased scatter at the lower irradiances. From the perspective of mathematical analysis, it is justified to eliminate data with AM > 2 because all CPV modules on-sun at NREL begin to have a negative relationship between power and AM in this range [3]. It is this negative relationship that is responsible for the bend in the CPV data shown in Figs 1-3. Ultimately, the compilation of information from Figs. 1-3 suggests that if data is temperature corrected and limits are placed on PWV and AOD it is possible to reduce the variation in a power rated at CSOC to about 5%. As power rating methods are considered hereafter, 5% represents a useful target for variation as applied to monthly data sets.

ASTM-2527 APPLIED TO MONTHLY DATA

In order to test a CPV module outdoors it first needs to be mounted on a tracker and aligned with the sun. At an ideal test site this could be done in a mid-morning hour and then I-V curves could be taken for the module in the midday hours to achieve a power rating. In reality the module might be mounted one day, aligned another, and then it be weeks before the needed data is acquired. With this in mind, it is a reasonable approach to autonomously gather data for multiple weeks and apply the statistical regression given in Eq.1 as specified in ASTM E 2527-06 [2].

$$P_{max}=DNI(a_1+a_2DNI+a_3T_{ambient}+a_4Wind) \qquad (1)$$

Figure 5 presents the variation in the ASTM power rating over multiple months for two CPV modules and one flat-plate module.

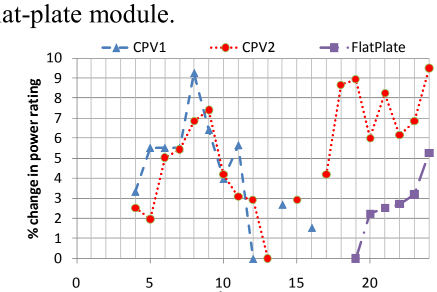

Fig.5 ASTM Power Rating Applied Monthly

The left axis in fig.5 shows the percent change in the power rating from the month with the lowest rating. For example, the flat-plate module shows its lowest power rating in month 19 (hence 0% change) while in month 20 the rating is about 2% higher than month 19. Fig. 5 shows that using ASTM-2527 can result in power ratings that vary by 10% for CPV and 5% for flat-plate. Although applying Eq. 1 is simple, the coefficients a_1, a_2, a_3, and a_4 fail to accurately measure actual relationship between power and meteorological conditions. For example, the flat-plate module shows increased performance in moving from hot summer months to cold winter months. Although power should increase as temperature decreases, the coefficients related to ambient temperature and wind speed fail to capture this known relationship, as evidenced by greater than a 130% variation in both coefficients over 6 months. The variation in regression coefficients can be more extreme with CPV modules. For example, the coefficient related to ambient temperature is positive in some months but negative in other months.

Fig. 5 also shows that both CPV modules have their lowest power ratings in the winter months. In these months, it is typically drier, the AM is higher than 1.5 (At NREL, December, January minimum AM is > 2, November, February minimum AM is > 1.7), and low ambient temperatures bring some CPV lenses out of optimum focus. It is worth noting, that some CPV modules show a lens related performance drop when the ambient temperature is less than 15C. Overall, the ASTM rating shows high variability in the winter months because the regression has no terms to account for changing spectral conditions or temperature dependent lens performance. Consider that if November through February were dropped from Fig. 5, CPV1 would have a variation of 7.6% and CPV2 would have a variation of 6.8%.

Although it would be ideal to complete a power rating on any sunny day and make corrections for temperature and spectral conditions it is probably necessary to avoid some extreme conditions. From this research and from past work [3], it is recommended that any data with an AM greater than 2 or PWV below 0.5 cm should be rejected. In general it is suggested that data for a CPV power rating should include measurements where AM 1.5 is realized in order to avoid extrapolation.

ALTERNATIVE APPROACHES TO ASTM-2527

Although a month-to-month variation of 7-10% is too high for an acceptable power rating procedure, analysis above suggested that filtering or applying corrections to the data could reduce variation. Filtering based on AM inadvertently removes the highly variable winter months and therefore makes it difficult to compare a corrective method to one that relies on heavy filtering. In order to do a meaningful comparison, data from November through February and all AM > 2 is excluded from all comparisons that follow.

In attempts to reduce variation in the monthly power rating many alternate equations and filtering requirements were considered. The key findings from these attempts are conveyed by examining the results from the following methods:

- ASTM1: added filtering $1.3 \leq AM \leq 1.7$
- ASTM2: using Eq.1 with a_5AM term added
- Regression1: $P_T = a_1DNI + a_2DNI^2 + a_3AM$
- Regression2: $P_{T,AM,PWV} = a_1DNI + a_2DNI^2$
- ISFOC: Power translation used by ISFOC [4], [5]
- ISFOC1: translation with added filtering $1.3 \leq AM \leq 1.7$
- ISFOC2: translation with correction for AM and PWV

P_T in "Regression1" represents the peak power point translated from the calculated cell temperature to a cell temperature that is representative of CSOC. Cell temperature is calculated using open circuit voltage (Voc), short circuit current (Isc), and cell specifications as by the "Voc,Isc Method" in use by Sandia National Laboratories [6]. With the cell temperature, the CSOC temperature, and temperature coefficient for III-V cells, the current and voltage are translated to CSOC to get P_T. $P_{T,AM,PWV}$ represents the peak power translation to a CSOC cell temperature plus additional corrections to AM of 1.5, and a PWV of 1.4 cm, as calculated by Equation 2.

$$P_{T,AM,PWV} = P_T - 0.01(AM-1.5)DNI\cdot A - 0.006(PWV-1.4)DNI\cdot A \quad (2)$$

In Eq.2, "A" is the module aperture area, DNI is measured, AM is calculated, and PWV is calculated from the dew point temperature. Eq.2 assumes that module efficiency increases 1% per AM unit and 0.6% per PWV unit. Although this assumption is not true for the entire range of AM and PWV it is approximate for the data under consideration [3]. The AM and PWV translation mentioned in method "ISFOC2", is achieved via Eq.2 by substituting the ISFOC power translation for P_T.

The results from applying alternatives "ASTM1" through "ISFOC2" to CPV1 and CPV2 are presented in Table 1 in comparison to ASTM-2527.

Table 1 Comparison of Power Rating Methods

Maximum Monthly Variation in Power Rating		
Method	*CPV1*	*CPV2*
ASTM-2527	7.6%	6.8%
"ASTM1"	8.7%	8.1%
"ASTM2"	8.0%	7.3%
"Regression1"	5.4%	6.7%
"Regression2"	4.2%	5.7%
"ISFOC"	6.9%	6.2%
"ISFOC1"	6.2%	6.1%
"ISFOC2"	2.9%	5.5%

DISCUSSION

Examining the results in Table 1, it is clear that attempts to adapt the ASTM method using additional filtering or by adding an AM term actually increased variation. Although not shown here, the same is true for filtering or adding terms to ASTM-2527, involving global normal irradiance (GNI), AOD, or PWV.

"Regression 1" represents the results of an effort to build a new CPV power rating regression from scratch. This was done by taking a year of CPV data from NREL and looking for the "best fit" as judged by lowest standard error and the Tstat on the included variables. Regressions were considered for both the measured power and P_T (the power translated to CSOC temperature) against linear and nonlinear terms using DNI, GNI, diffuse irradiance, wind speed, ambient temperature, heat sink temperature, AM, PWV, and AOD. $P_T=a_1DNI+a_2DNI^2+a_3AM+a_4PWV$ was found to be the "best fit" regression with a standard error of 1.8%, while PWV had the lowest Tstat of 7.7 and all other variables had Tstats in the range of 15 to 25. This "best fit" regression was applied to monthly data sets and it was quickly found that PWV was not relevant on a monthly basis, hence why "Regression1" in Table 1 does not include PWV. In comparison to ASTM, "Regression1" reduces variation for CPV1 but does little for CPV2. "Regression1" is ultimately given a failing mark because of the marginal improvement for CPV2 and observations that the AM coefficient is positive in some months while negative in others.

"Regression2" is more a corrective or translation approach to computing a power rating. Eq. 2 shows that corrections have been made for cell temperature, AM, and PWV while a regression is only used to find the relationship between corrected power and DNI. The results of 4.2% variation for CPV1 and 5.7% for CPV2 suggest that more translation/correction is beneficial compared to regression.

With evidence supporting a translation approach, it is valuable to consider the full translation to CSOC that ISFOC has been using on a system level for several years [4]. In the ISFOC method, a measured power is translated to CSOC using I-V measurements, cell specifications, and cell temperature via a heat sink temperature measurement (assuming knowledge of the thermal resistance between the cell and heat sink). The translation is typically done for an entire I-V curve and then the new peak power point is found. The ISFOC approach has been applied to NREL data both translating the entire I-V curve and translating just the original peak power point. It was found that the uncertainty associated with translating only the peak power point is at least an order of magnitude less than the uncertainty of the monthly power ratings being examined. To simplify data processing, this method is used in some cases. It also must be stated that NREL does not have knowledge of the thermal resistance between the heat sink and the cell for all CPV modules under test. For those modules with a known thermal resistance, a comparison was done between the cell temperature calculated via the "Voc,Isc Method" and that using the heat sink measurement. On average there is less than a 2C difference between each approach. To be consistent, the "Voc,Isc Method" is used to calculate cell temperature for all modules under examination. The monthly power rating is computed by translating all acceptable I-V curves for the given month and then averaging the results.

Table 1 shows that ISFOC translation results in a 6.9% variation for CPV1 and 6.2% variation for CPV2. As these results are less than a percent better than the basic ASTM method, this suggests that filtering and additional corrections are worth considering. "ISFOC1", which only accepts I-V curves with AM between 1.3 and 1.7, resulted in a slight improvement over ISFOC's specified filtering. Finally, "ISFOC2" applies corrections for AM and PWV based on Eq.2. Ultimately the "ISFOC2" method resulted in the lowest variation for a monthly power rating for both CPV1 and CPV2.

CONCLUSIONS

2009/2010 data, filtered to meet ASTM-2527 conditions, have been examined for multiple CPV modules on-sun at NREL. A July to December data set shows CPV measured power can vary by as much as 10% at a given DNI. For the same data set, applying a temperature correction, limiting PWV to 1-3 cm, and limiting AOD to 0.06-0.135 reduces variation to 5%.

With the larger data set providing perspective, attempts were made to calculate a monthly outdoor CPV power rating that would vary by less than 5%. ASTM-2527 was used as a baseline, while additional filtering, alternate regressions, and translations were considered in efforts to minimize month-to-month variation.

Pure Regression-based approaches performed poorly while approaches that included correction for temperature, AM and PWV provided the best results. "Regression2", which corrected for all but DNI, had a variation of 4.2-5.7%. "ISFOC2", which combined the ISFOC power translation with corrections for AM and PWV, had a variation of 2.9-5.5%.

The overall investigation led to several key suggestions/recommendations:

1) Exclude AM >2, PWV <0.5 from power rating data.
2) Exclude months that AM 1.5 does not occur.

3) PWV and AM should not be ignored.
4) Default to translation over regression approach.
5) Do not ignore temperature effects on lenses.

Future work should apply translation-based approaches to more modules and over longer time periods in order to confirm the results presented here. Efforts should be made to refine corrections for AM and PWV or to apply alternate corrections as data become available that improve ability to characterize the spectral conditions. Finally, corrections for variations in lens performance should be considered.

ACKNOWLEDGMENTS

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