An Investigation into Spectral Parameters as they Impact CPV Module Performance

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An Investigation into Spectral Parameters as they Impact CPV Module Performance

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Abstract: The CPV industry is well aware that performance of triple junction cells depends on spectral conditions but there is a lack of data quantifying this spectral dependence at the module level. This paper explores the impact of precipitable water vapor, aerosol optical depth (AOD), and optical air mass on multiple CPV module technologies on-sun in Golden, CO.

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INTRODUCTION

It is well known that triple junction CPV cell performance depends on spectral conditions, and, therefore, atmospheric conditions such as aerosol optical depth (AOD), precipitable water vapor (PWV), and optical air mass (AM) can have an impact on cell and module performance [1]. Although improved models are needed to accurately predict energy production for CPV systems, it is not clear what, if any, spectral parameters should be included in these models. As spectral data is not as readily available, one must justify requiring this data by a significant increase in model accuracy. To further compound this issue, CPV system technology varies significantly, and it is probable that spectral data could improve energy predictions for one technology but have little impact on alternate technology.

This paper explores the impact of AOD (at 500 nm) PWV, and optical AM on module performance, in conjunction with the SMARTS spectral model [2], cell quantum efficiency (QE) data (InGaP/InGaAs/Ge optimized for a G173/AM 1.5 spectrum), and spectral measurements from a PG S-100 Direct Normal Spectral Radiometer. Integrating the QE data with both modeled and measured spectra provides a means to predict changes in module current as AOD, PWV, and optical AM change.

This paper proceeds as follows: First, spectral sensitivity in CPV modules is examined by analyzing short circuit current, Isc, divided by direct normal irradiance, DNI, as spectral parameters change. Percent changes in Isc/DNI are presented from both a modeling perspective and using module data. CPV module performance is then presented through metrics such as the PVUSA rating, (ASTM E-2527 [3]), performance ratio, PR, [4], and DNI weighted module efficiency. Deviations in annual energy production are predicted based on module level spectral sensitivity as quantified through an optical AM based correction factor. Finally conclusions are drawn and future work is discussed.

SPECTRAL SENSITIVITY OF ISC/DNI

It is useful to begin an analysis of the spectral sensitivity of CPV modules by briefly mentioning characteristics of an InGaP/InGaAs/Ge cell in relation to the solar spectrum and key spectral parameters. The InGaP (top junction) is generally responsive in the range of 350-700 nm, the InGaAs (middle junction) from 500-1000 nm, and the Ge (bottom junction) from 800-1800 nm. The three junctions are wired in series and therefore the cell operates based on the junction that is generating the least current. Manufactures typically design cells such that the top and middle junctions alternate in the role of limiting current while the bottom junction always has surplus current. The top and middle junctions are grown to be current matched for the G173/AM1.5 direct reference spectrum, a design point that is suggested for optimum energy production at many CPV-appropriate sites [5].

The spectrum is very dynamic, and changes in optical AM, PWV, and AOD all impact CPV performance. Optical AM, the relative path length through the atmosphere, varies from 1 to 5 when CPV produces the majority of its energy. As optical AM increases, there is an increased Rayleigh scattering of blue light and the top junction predominantly loses current. PWV, cm of condensed water vapor in the vertical direction, absorbs solar radiation in bands around 720, 820, 940, 1100, 1380, 1870, and 3200 nm. Absorption bands corresponding to the bottom junction are the strongest, but because the bottom junction does not limit this device's performance, PWV has little effect on cell performance. However, absorption by water vapor does decrease the measured DNI. Consequently, as PWV increases, DNI decreases more than power, resulting in an increase in efficiency. It is interesting to note that changes in PWV have stronger impact in dry climates due to the fact that an increase from 0 to 0.4cm of PWV decreases solar radiation by 10% while an increase from 0.4 cm to 4 cm is required to decrease radiation another 10% [6]. AOD measurements quantify the number of particles/aerosols in the vertical direction that result in radiation attenuation in the range of 400 to 2000 nm. The rate of attenuation decreases with wavelength but is a complex function of quantity and size distribution of particles [6]. An increase in AOD typically results in the top junction decreasing in current more than the middle junction.

SMARTS is a readily available tool that can be used to predict the effects of changing optical AM, PWV, and AOD on triple junction cell performance. SMARTS v2.9.5 is used in its default settings with the exception of a pressure of 840 mB and altitude of 1.6km for Golden, CO. Figure 1 displays a family of curves that predicts how Isc/DNI changes as optical AM and PWV vary with AOD fixed at 0.084. Figure 2 predicts how Isc/DNI changes as optical AM and AOD vary with PWV fixed at 1.4cm. The curves in Figures 1 and 2 were generated by integrating each SMARTS spectrum with QE data from the top two junctions of a G173 optimized cell. The lesser of the two currents is then taken and a percent change was calculated based on the current predicted for optical AM1.5, PWV of 1.4 cm, and an AOD of 0.084. This procedure neglects the effective transfer of photocurrent to lower junctions when excess photocarriers recombine radiatively in an upper junction.

Figures 1 and 2 give an indication of how much Isc/DNI can change as the spectral conditions swing from one extreme to the other, but this is somewhat misleading as many CPV sites are unlikely to see these entire ranges. In Golden, Colorado (from 5/1/2009 to 2/1/2010) the bulk of PWV measurements have fallen in the range of 0.3 to 2.5 cm, while AOD has approximately ranged from 0.02 to 0.2.

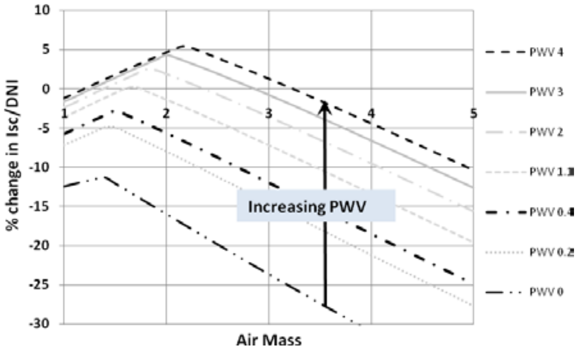

FIGURE 1. As PWV increases, Isc/DNI increases. Isc/DNI increase is stronger on the right side of the AM response peak (top junction limited). If PWV increases from 0 to 0.4 cm, Isc/DNI increases 10% while an increase in PWV from 0.4 to 4 cm results in a similar 10-12% increase in Isc/DNI.

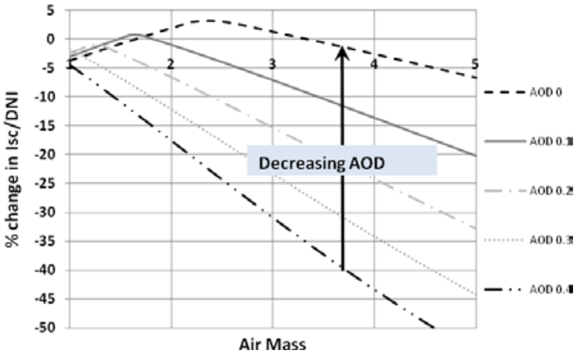

FIGURE 2. When to the right of the AM response peak (top junction limited), Isc/DNI increases as AOD decreases. When to the left of the AM response peak (middle junction limited), AOD change has little impact on cell performance.

Figure 3 plots measurements taken for a module from May, 2009 to February, 2010 in Golden, CO. The dashed lines in Fig. 3 are the upper and lower boundaries of change in Isc/DNI as predicted by SMARTS integrated with cell QE data adjusted to 57C, (average cell temperature for data set in Fig. 3).

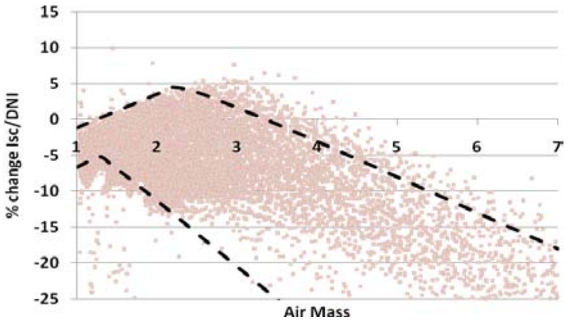

FIGURE 3. Module data taken at Golden, CO. Dashed lines represent predicted boundaries for data using SMARTS, cell QE @ 57C, and measured ranges for PWV, and AOD.

Although modeling provides a reasonable approximation for the boundaries to the 9-month data set, using the same approach to predict changes to Isc/DNI over the course of a sunny day is more problematic. Figure 4 presents Isc/DNI and AOD data for 8/20/2009 with an overlay of predictions using SMARTS spectra integrated with cell QE information.

The data for the module shows that the Isc/DNI is rising in the early morning, peaks at about AM2.5, and then declines until AM1 or solar noon. If spectral conditions and other meteorological conditions remained constant, it would be expected that the Isc/DNI would retrace the same curve for the second half of the day. In fig.4, there is a shift of the curve near solar noon and at the same time AOD increases from 0.1 to 0.15. Although it is not shown on fig.4, the cell temperature has also climbed approximately 5-10C and about 2 hours before noon the PWV dropped from 1.8 to 1.5 cm. The solid line represents the predicted Isc/DNI for the morning conditions and the dashed line for afternoon conditions. The 5-10C cell temperature change has been neglected in the prediction and potentially could introduce a 1% change in Isc/DNI.

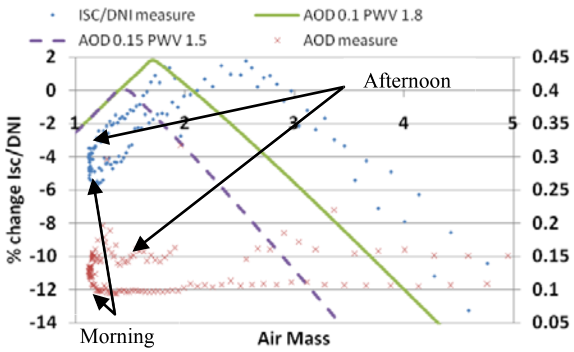

FIGURE 4. Isc/DNI (left axis) and AOD (right axis) data for 8/20/2009. The solid line is predicted change in Isc/DNI for morning spectral conditions while the dashed line represents afternoon spectral conditions.

The data and predictions in fig.4 trigger many questions. First, why is the module Isc/DNI peaking near AM2.5 while the cell prediction suggests it should occur between AM1.4 and AM1.7. In further exploring this question, 28 individual sunny days were examined across the entire data set presented in fig.3. For these 28 days Isc/DNI peaked in a range from AM2.4 to AM3.4, with most days also presenting a shift in the AM peak as spectral conditions varied from morning to afternoon. The magnitude of this range (1AM unit) is consistent with the magnitude between the peaks of the dashed lines shown in fig.3 (AM1.2 to AM2.2). Across the 28 days, there is also a rightward shift of about 1.2 AM units from the modeled to the measured peak. It is speculated that module optics disproportionately filter red light, hence the module optical AM peak is to the right of the predicted peak for bare cells. Discussions with the manufacturer confirm they have seen a similar red shift and have since modified optics in the latest production module.

Module optics may explain some of the lack of alignment from left to right between data and prediction, but the model completely fails to explain the increase in the Isc/DNI around solar noon as AOD increases. Looking closer at the module data for the time around solar noon, Isc is increasing while DNI is decreasing. This suggests that the increase in AOD is decreasing DNI, (dominating over the PWV decrease), in the blue region but not reducing Isc as the cell is middle junction limited. At the same time the PWV decrease can allow more light to the middle cell due to bands at 720, 820, and 940 nm. This possible increase in light to the middle cell is additive with an increase in Isc as cell temperature rises.

Data from a spectral radiometer provides another means to predict Isc/DNI for 8/20/2009. Rather than integrating the cell QE with SMARTS spectra it can be integrated with the measured spectra. Isc/DNI data is again plotted in fig.5 but this time against predictions using the measured spectra.

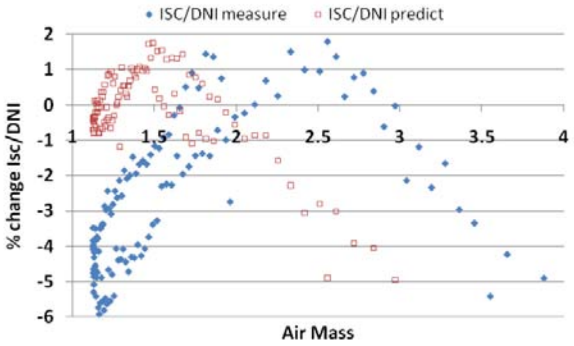

FIGURE 5. Module data plotted with Isc/DNI predicted using measured spectra, cell QE, and measured DNI

Calculations for Isc/DNI using the measured spectra clearly predict the direction of the shift at solar noon but with a decreased magnitude. The decreased magnitude could be due to neglected changes in cell temperature and effects from the module optics. The calculation using SMARTS spectra could have failed to predict the shift at noon for several reasons. First, the model requires various spectral inputs of which only PWV and AOD were varied. As with any model, the outputs are only as good as the inputs. In this case the differences in PWV and AOD seen in the morning and afternoon are in the same range as the uncertainties for these measurements. To compound this further, AOD modeling is very complex and model uncertainty or model choice can introduce error comparable to the 2% shift in Isc/DNI near solar noon.

MODULE PERFORMANCE

CPV modules are built to generate energy and therefore studying the spectral sensitivity of Isc is only a step in the process. Although studying Isc provides a means to avoid the voltage temperature dependence, care must be taken in applying Isc results to module efficiency. It has been documented in the literature that a decrease in Isc/DNI has less than a 1:1 relationship with efficiency [7]. This reduced effect on efficiency is due to fill factor, FF, increasing as current mismatch increases in multi-junction cells. This relationship has been documented at the cell level and is confirmed for three distinct modules shown in fig.6. The data in fig.6 comes from modules that use both refractive and reflective optics and the number of cells in series varies widely.

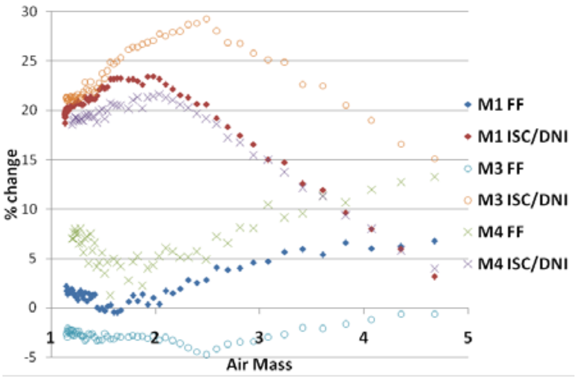

FIGURE 6. (top) %change in ISC/DNI for 3 distinct modules (bottom) %change in FF for the same modules. ISC/DNI peaks as FF reaches a minimum. Data has been shifted in the vertical direction for readability.

To quantify the impact of spectral variations, a simple approach is used to examine module performance. Monthly data sets are analyzed for three modules that have been on-sun for multiple months in Golden, CO. Table 1 presents the PVUSA rating, the performance ratio, and the DNI weighted efficiency, (ΣηDNI/ΣDNI), for each month. The variation in these monthly metrics provides some gauge of performance spectral sensitivity. Golden, CO can have summer months with averages of 1.9 cm PWV and 0.135 AOD, while winter averages are near 0.45 cm PWV and 0.075 AOD. Keep in mind that these modules have not been on sun long enough to rule out degradation mechanisms. There is approximately a 5-10% variation from the high months to the low months for the metrics given in table 1. This is lower than the 15% variation in Isc/DNI shown in fig.3 and is consistent with the relationship between Isc/DNI and FF as shown in fig.6.

TABLE 1. Monthly PVUSA power rating (Watts), DNI weighted efficiency (η), and performance ratio (P.R.) for 3 distinct module technologies on-sun at Golden, CO

		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
M 1	Watts	69.5	71.3	72.0	72.5	72.0	69.9	68.7	70.9	67.9
	η	23.7	24.4	24.8	25.0	24.9	24.4	23.5	21.7	22.3
	P.R.	.928	.958	.972	.982	.975	.957	.922	.853	.873
M 2	Watts	77.2	78.4	78.9	79.3	82.1	79.1	78.1	81.1	75.9
	η	18.8	19.4	19.2	19.0	19.4	19.6	19.0	19.3	19.3
	P.R.	.944	.974	.961	.951	.972	.981	.952	.965	.968
M 3	Watts	111	110	110	107	107	105	104	106	99.5
	η	22.1	21.9	21.8	24.5	21.4	21.4	20.8	20.5	20.5
	P.R.	.987	.979	.973	.960	.958	.957	.930	.919	.919

ENERGY COMPARISON

An effort was made to model the efficiency of the three modules in Table 1 based on PWV, optical AM, AOD, and cell temperature. With more information needed to calculate cell temperature for two of the modules, and the uncertainties in the PWV and AOD measurements, a simple approach was taken using only the optical AM correction in equation 1.

$$\textit{Rated Efficiency} - a|AM-b| \tag{1}$$

This simple optical AM correction was fit to nine months of data for each of the modules and then used in an annual energy comparison. Table 2 contains the AM corrections for the three modules, but assumes each module has the same baseline efficiency. This provides a means to compare energy production differences from spectral sensitivity alone.

TABLE 2. Annual energy comparison using optical AM based spectral sensitivity from 3 module data sets

2009	M1 25% - 1.6|AM-1.7|	M2 25% - 1|AM-2.8|	M3 25% - 0.95|AM-2.5|	Fixed 25%
Q1 kwh	118.1	120.7	121.7	127.4
Q2 kwh	113.7	113.2	114.5	120.5
Q3 kwh	130.4	130.0	131.5	138.3
Q4 kwh	97.8	102.0	102.6	107.3
total kwh	460.05	465.95	470.3	493.5

The energies shown in Table 2 were calculated using the optical AM corrections, the 2009 one-minute average DNI from NREL, and a module area of one square meter. The results show that there is approximately a 7% difference in energy produced from a fixed efficiency and module 1 and about 2.2% difference between module 1 and 3.

CONCLUSIONS

This work examines the spectral sensitivity of CPV modules with triple-junction cells on-sun for multiple months in Golden, CO. The SMARTS model is used with QE data, optical AM, PWV, and AOD measurements to predict variation in Isc/DNI over 9 months. Ultimately this approach provides a reasonable estimate of long term variation in Isc/DNI. When SMARTS is used in the same approach to predict intra-day changes the results are less useful. This is likely due to small intra-day changes in PWV and AOD being within the measurement uncertainty of these parameters coupled with uncertainties and assumptions made when applying the SMARTS model. At the same time, using measured spectra rather than SMARTS spectra, intra-day modeling indicated the correct movements in Isc/DNI but with a reduced magnitude.

In examining CPV module performance, data show clearly defined AM response peaks for Isc/DNI and efficiency while confirming that FF is minimized when Isc/DNI peaks. The module metrics, PVUSA power ratings, Performance Ratio, and DNI weighted efficiency, all show monthly variations on the order of 5-10%, while Isc/DNI shows variation of 15%. In a simple approach, the overall spectral sensitivity of 3 modules is quantified by fitting an AM correction factor to 9 months of data and then applying these correction factors in a yearly energy prediction. Ultimately, the AM correction factor results in a 7% drop in annual energy over a fixed-efficiency module, and 2% difference between CPV modules with the differing spectral sensitivity.

Future work calls for continuing to gather module data as a measure against degradation and to verify that the spectral sensitivities suggested in this report are repeatable. As more spectral radiometer data becomes available, this will be used to further investigate the spectral parameters discussed in this report. Eventually, it is hoped that this work can be expanded to compare CPV module data to system level data.

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