Spectrally Selective Sensors for PV System Performance Monitoring

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***Abstract* — The main purpose of PV system performance monitoring is to determine whether the system is operating as expected. This requires measuring the actual output of the system as well as the conditions under which it is operating. Solar radiation intensity in the plane of the array (POA) is by far the most important operating condition and is the basis for calculating performance ratios (PR). However, differences in spectral and directional response between pyranometers and PV modules lead to intraday as well as seasonal fluctuations in the performance ratio, even though the system may be operating without faults or degradation.**

For c-Si PV systems, a reference cell can be used instead of (or in addition to) a pyranometer to measure POA irradiance. Since reference cells have spectral and directional responses that are similar to PV modules, their output signals correlate better with system output. As a result, it is becomes easier to identify abnormal system operation.

In this paper, we present a practical alternative to using a spectrally matched reference cell for measuring POA irradiance. The method uses dual sensors with different spectral responses whose outputs are combined to produce a composite signal. That composite signal can effectively match the spectral response of any PV module type over a wide range of irradiance conditions. As a result, this method makes possible the rapid and accurate detection of abnormal system operation for thin-film systems.

***Index Terms* — performance monitoring, photovoltaic systems, spectral mismatch, pyranometer, spectrometer, reference cell.**

I. Introduction

The fundamental purpose of PV system quality monitoring is to measure the operating conditions of a PV system together with the actual output of the system, and determine whether the system is operating as expected. Yield expectations can result from:

- System simulation based on as-built system parameters
- Comparison with records of past performance
- Comparison with other systems

In all cases, the actual operating conditions must be taken into account in order to make meaningful comparisons.

Solar radiation intensity measured in the plane of the array (POA) is the most important operating condition, but explaining variations in PV system yield using only this measurement is challenging because pyranometers and PV modules respond differently to incoming solar radiation [1]. The main differences are:

- Pyranometers have a broad-band spectral response covering virtually the whole solar spectrum, whereas PV cells respond to only a limited range. The range is different for different cell materials, and varies with temperature.
- Pyranometers are designed to absorb light equally well regardless of the direction it comes from, and do this quite well. PV modules are also designed with this goal, but in practice the goal is not attained. The amount of light that is reflected depends on the angle of incidence.
- Pyranometers are designed not to be influenced by the ambient temperature, whereas PV cell efficiency changes with temperature. The magnitude of this dependency varies for different cell technologies.

In practice, it is difficult to distinguish between these three factors since there are correlations between the position of the sun in the sky, the spectral content of the solar radiation, and the ambient temperature.

To more accurately capture the operating conditions of a PV system, therefore, additional measurements are required. Ambient and/or cell temperature can be measured with little effort, and the module temperature coefficients are then used to adjust expected output. However, spectral and angle of incidence effects are not so easy to measure and to adjust for.

For c-Si PV systems, a reference cell can be used instead of (or in addition to) a pyranometer to measure POA irradiance. Such a reference cell has a spectral and angular response that is similar to the PV modules. The output signal of the reference cell (short circuit current) therefore has a very strong correlation with the PV system output, especially after a temperature correction is made. Thus it becomes much easier to compare measured performance with past performance, and detect changes or problems quickly.

For monitoring a-Si systems, a c-Si reference cell can be combined with an optical filter of type KG3 to mimic the PV module spectral response. This is done because a-Si reference cells cannot provide the required long-term stability. For other thin-film technologies matching reference cells are not commonly available—and with the many types of cells on the market it is not expected that an appropriate, stable reference cell for each type will become commonly available in the future. Our objective, therefore, is to develop a practical alternative to using spectrally matched reference cells for the purpose of monitoring the performance of thin film PV systems.

II. Method

The method presented in this paper uses multiple sensors with different spectral responses. The idea is based on the fact that the spectral distribution of solar radiation is not arbitrary, but varies systematically as a result of interactions with the atmosphere. Several methods have been proposed to characterize the range of naturally occurring spectral distributions with simple metrics such as the Average Photon Energy (APE) [2] or the "S" factor [3]. These metrics are essentially indicators of the balance between energy content at higher wavelengths versus at lower wavelengths. While these one-dimensional metrics cannot represent all spectral details, this shortcoming is not critical in the context of PV system monitoring. PV cells themselves, regardless of the technology, respond to broad ranges of wavelengths.

Our hypothesis is that we can "measure" the distribution (or balance) of typical solar spectra directly by using two sensors, each responding to a different range of wavelengths. Furthermore, we postulate that the output of a PV module (S_{module}) with a different spectral response from either of those two sensors can be predicted by a composite signal that is calculated simply as a weighted sum of the two sensor signals:

$$\hat{S}_{module} = a_1 \cdot S_{sensor\,1} + a_2 \cdot S_{sensor\,2} \qquad (1)$$

Suitable sensor pairs for this purpose would have strongly different and preferably non-overlapping spectral responses, however if the underlying principle holds, other combinations may be used as well – such as one broadband pyranometer and one narrow-band sensor. In fact, since pyranometers and silicon reference cells are the standard instruments for PV system monitoring, we focus especially on evaluating the benefit of adding a second spectrally selective sensor to one of these two instruments.

Validation of our hypothesis is done in two ways. First, the theoretical output of different sensors and module types are calculated from measured spectra. The two weights $a1$ and $a2$ are then determined by linear regression minimizing the sum of the squares of the error ($\hat{S}_{module}$ - S_{module}). Since these calculations all derive from the same instrument, the spectrometer, this validation is in principle unaffected by angle-of-incidence effects. The error is purely a measure of ability of the composite signal to represent the spectral response of the module.

The second validation uses the actual sensor and module measurements. To maintain the focus on spectral effects, the angle-of-incidence effects are first corrected, and then the sensor weights are again determined by regression.

The evaluation consists of a comparison of RMS errors. The base case for the comparisons uses a single sensor, either a pyranometer or a Si reference cell, to predict module output. Adding a second sensor and using the composite signal to predict module output reduces the RMS error from the base case.

Mean bias errors are not evaluated as they are primarily related to the calibration of the sensors. In fact, all PV module measurements are scaled to the unit-less range 0–1000, and all sensor signals are scaled to eliminate mean bias errors.

III. Data Collection

The equipment used for this study consists of the following: one pyranometer and a pair of spectrometers to characterize the incoming solar radiation; several spectrally selective sensors; and one CdTe module whose short-circuit current is measured. All sensors and modules are mounted in the same plane, tilted 30° and oriented due south, and located on the roof of the main Fraunhofer ISE building in Freiburg, Germany. Data collected during the period August, 2011 to March, 2012 are used for this study.

Table I lists the most important sensor details. Most of the measurements are temperature compensated. The exceptions are the Lux sensor, which is specified as having a very low temperature dependency, and the Black Photon prototype sensors, for which we do not have details yet. The spectral ranges in the table are very approximate, but much more detail is shown in Fig. 1.

Table I. Sensors

Instrument	Model	Spectral range [nm]	Short identifier
Spectrometers	EKO MS710 & MS712	~335 – 1700	
Pyranometer	Kipp & Zonen CMP21	~285 – 2800	Pyr
Si Reference Cell	Mencke & Tegtmeyer Si-02-Pt100-K	~400 – 1100	Si
Si Reference Cell with KG3 filter	ISE Brachmann	~400 – 800	SiKG3
Lux Sensor	EKO ML-020S-0	~380 – 780	Lux
GaInP top junction	Black Photon SE-044-TLM	~350 – 700	GaTop
GaInAs middle junction	Black Photon SE-045-MLM	~650 – 900	GaMid

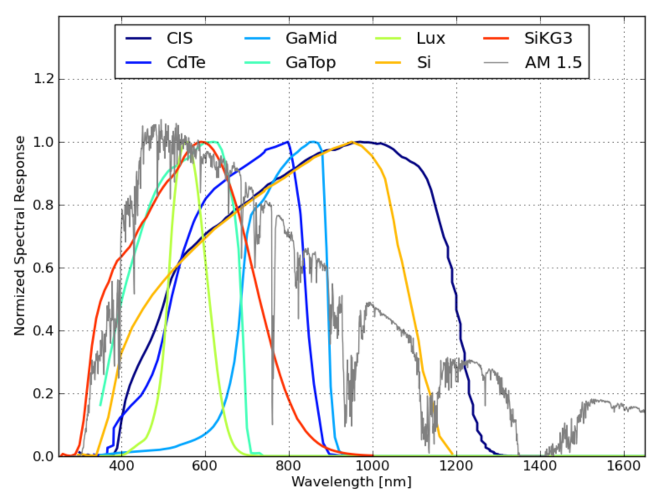

Fig. 1. Spectral response curves for the sensors and two module types

Two thin-film module types are used as examples in the study: CdTe and CIS. For both types we calculate the theoretical output from the measured spectra, but we only have measured output in the form of short circuit current for the CdTe module.

IV. Data Preparation and Selection

The preparation of the data consists of several steps. The first step is to select a suitable subset for analysis. We manually selected one clear, one partly cloudy and one overcast day in each month from August, 2011 to March, 2012 for a total of 24 days. This covers a broad range of conditions for our site.

The second step uses the spectral radiation measurements in combination with the known spectral response curves to calculate the theoretical output of each of the sensors and PV module types. This is done by summing the products of the radiation intensity and spectral sensitivity at each recorded wavelength over the range of interest.

The third step is to correct the sensor data for non-ideal cosine response. The deviation from ideal cosine response is expressed as a function of incidence angle based on information obtained from the manufacturers, from published reports, and tests done at our institute. For the PV module a typical cosine response for low-iron glass covered module is used. Dividing a signal by a sensor's cosine-error function effectively cancels or corrects the cosine error. However since this error primarily affects direct radiation, the correction must only be applied to the portion of the signal that represents direct radiation. For this purpose the direct/diffuse ratio was obtained from an adjacent weather station.

During the initial analysis it was noted that not all sensors were perfectly aligned in the same plane. A small error in orientation toward the East was apparent as a higher signal in the morning and lower in the afternoon compared to the correctly oriented sensors. This orientation error was corrected by a factor $\cos(aoi_{nominal})/\cos(aoi_{actual})$ applied to the direct radiation portion of the sensor signal.

The uncertainty in the corrections for both cosine response and orientation rapidly increases as the incidence angle approaches 90º. At the same time the relevance of the data at high incidence angles is minimal, therefore a further filtering of the data was carried out to remove data points where the angle-of-incidence is greater than 75°. Data points where the sun elevation is less than 10° were also discarded since in most systems some form of shading will occur at such low angles.

Finally, data points taken at times of large irradiance fluctuations were removed. Such fluctuations are principally caused by passing clouds, to which different sensors respond differently depending on their size, position, intrinsic time constant and frequency of sampling. All data were summarized to five-minute averages, discarding those where the standard deviation of the five one-minute averages exceeded 25 on the normalized scale. On a sunny day this standard deviation remains below 10.

At this point we have the two sets of data needed for the validation: the theoretical values calculated from the spectral data, and the cosine-corrected measurements. For the CdTe module technology we have both theoretical values and measurements, whereas for the CIS type we have only the theoretical output.

V. Results

A. Effect of Cosine-Correction

The primary focus of this study is on spectral response issues. In order to sharpen this focus, all measurements were cosine-corrected as described in the previous section. It is important to note that this correction step alone has a very positive influence on the correlation between sensor and module output. In fact, in the base case scenario where a pyranometer is used to monitor a CdTe module, cosine-correction reduces the RMS error by 27%. In the other base case with a silicon reference cell monitoring a CdTe module, the RMS error is reduced by 11%. The improvement in the second case is smaller, of course, because the cosine response of the reference cell and module are not so different from each other.

The improvements attributed to the ability of the dual sensor method to match module spectral response are separate from (and in addition to) the cosine-correction benefit.

B. Evaluation of the Base Cases

The scenario we wish to improve upon is the monitoring of a thin-film module technology with a single sensor, such as a pyranometer or a silicon reference cell. We therefore first determine the RMS errors for each of those cases. The six results, expressed on the unitless scale of 0 to 1000, are shown in Table II.

Table II. RMS errors for base cases using a single sensor

Module output	RMS error using Pyranometer	RMS error using Reference Cell
CdTe – theoretical response calculated from spectra	8.2	6.7
CdTe – cosine-corrected measurements	10.2	7.8
CIS – theoretical response calculated from spectra	6.9	4.8

C. Evaluation of Dual-Sensor Combinations

Six different sensors can be paired in 15 different ways. Adding the constraint that one must be a pyranometer or a silicon reference cell this number is reduced to nine pairs: five with the pyranometer as a base case; and four with the reference cell as a base case.

For each of the nine sensor pairs, weighted-average composite signals are calculated as per equation (1) to estimate or predict module output. For the two theoretical module outputs the theoretical sensors signals are used; and for the one measured module output the measured sensor signals are used. Thus, a total of 27 scenarios are evaluated, for which the results are presented in Table III through Table V.

TABLE III. PREDICTING THE OUTPUT OF A CDTE MODULE – THEORETICAL RESULTS FROM RECORDED SPECTRA

Base case sensor	Second sensor	Param a1	Param a2	Base case RMS error	Dual sensor RMS error	Reduction of RMS error
Pyr#	Si#	-0.032	1.032	8.2	6.7	-19%
Pyr#	SiKG3#	0.690	0.311	8.2	6.2	-25%
Pyr#	Lux#	0.658	0.342	8.2	5.8	-30%
Pyr#	GaTop#	0.741	0.259	8.2	6.4	-22%
Pyr#	GaMid#	0.817	0.184	8.2	7.8	-5%
Si#	SiKG3#	0.706	0.294	6.7	3.7	-45%
Si#	Lux#	0.679	0.321	6.7	3.1	-53%
Si#	GaTop#	0.743	0.257	6.7	3.7	-45%
Si#	GaMid#	1.170	-0.170	6.7	6.4	-5%

TABLE IV. PREDICTING THE OUTPUT OF A CDTE MODULE – COSINE-CORRECTED MEASUREMENTS

Base case sensor	Second sensor	Param a1	Param a2	Base case RMS error	Dual sensor RMS error	Reduction of RMS error
Pyr	Si	-0.159	1.159	10.2	7.7	-25%
Pyr	SiKG3	0.648	0.352	10.2	7.9	-23%
Pyr	Lux	0.831	0.170	10.2	8.4	-17%
Pyr	GaTop	0.821	0.180	10.2	8.3	-19%
Pyr	GaMid	0.940	0.061	10.2	10.1	-1%
Si	SiKG3	0.732	0.268	7.8	6.1	-22%
Si	Lux	0.886	0.115	7.8	6.7	-14%
Si	GaTop	0.851	0.150	7.8	6.2	-21%
Si	GaMid	1.039	-0.040	7.8	7.7	-1%

TABLE V. PREDICTING THE OUTPUT OF A CIS MODULE – THEORETICAL RESULTS FROM RECORDED SPECTRA

Base case sensor	Second sensor	Param a1	Param a2	Base case RMS error	Dual sensor RMS error	Reduction of RMS error
Pyr#	Si#	-0.020	1.020	6.9	4.7	-31%
Pyr#	SiKG3#	1.278	-0.279	6.9	4.5	-35%
Pyr#	Lux#	1.281	-0.282	6.9	4.7	-31%
Pyr#	GaTop#	1.256	-0.256	6.9	4.3	-38%
Pyr#	GaMid#	0.615	0.385	6.9	3.2	-54%
Si#	SiKG3#	1.235	-0.236	4.8	1.4	-70%
Si#	Lux#	1.237	-0.237	4.8	1.6	-66%
Si#	GaTop#	1.204	-0.205	4.8	1.5	-68%
Si#	GaMid#	0.800	0.200	4.8	4.1	-15%

In each of the tables, the best sensor combinations are highlighted, and these results are presented in more detail in Fig. 2 through Fig. 7. The top portion of each figure plots the sensor outputs against the module output, and the scatter in these plots gives a visual indication of the deviation between them. The blue points represent the base case sensor, the red points are for the second sensor, and the green points for the composite sensor signal. The deviation for each is shown on a magnified scale in the three smaller plots below. The reduction in RMS error that is listed in the table is seen as a reduction in scatter between the blue and green plots.

VI. DISCUSSION

In the three summary tables our measure of success is the reduction of RMS error achieved when moving from single sensor (either Pyr or Si) to dual sensor monitoring. Since we want to focus on the spectral effects, both single-sensor and dual sensor variations are cosine-corrected. The cosine-correction technique is a useful by-product of this study that also provides benefits when used with a single sensor.

In the base cases (Table II) we observe here that using measured signals for CdTe leads to higher RMS errors than using the theoretical signals calculated from the spectra. This suggests that the measured signals have a source of error besides spectral mismatch. Although the cosine correction was very effective, we know it is not perfect and therefore continues to contribute to the observed errors.

Comparing the three results sets for the dual sensors, we see that the three sensors SiKG3, Lux and GaTop provide roughly similar benefits, and their weighting parameters are also similar. That is because all three are sensitive in the shorter wavelength region of the solar spectrum. Looking more closely at the CdTe results, the spectrum calculations suggest that the Lux sensor should be the more effective of the three, which could be due to its narrower SR range; however, the cosine-corrected measurements show the SiKG3 performing better. We attribute this to poor quality data for the Lux sensor's cosine response, and which led to an inadequate cosine correction.

There are a few cases were one of the weighting parameters is negative. While this may seem odd at first, it simply indicates that a sensor's response to spectral shifts is opposite to the module's response.

The pyranometer, both alone and in combination with another sensor, shows greater RMS errors than the Si sensor alone or in combination. The fact that the SR of the Si sensor is closer than the pyranometer to both the CdTe and CIS modules gives the Si sensor an intrinsic advantage in predicting module output. The pyranometer on the other hand offers a more universal measurement that can also be compared to meteorological records.

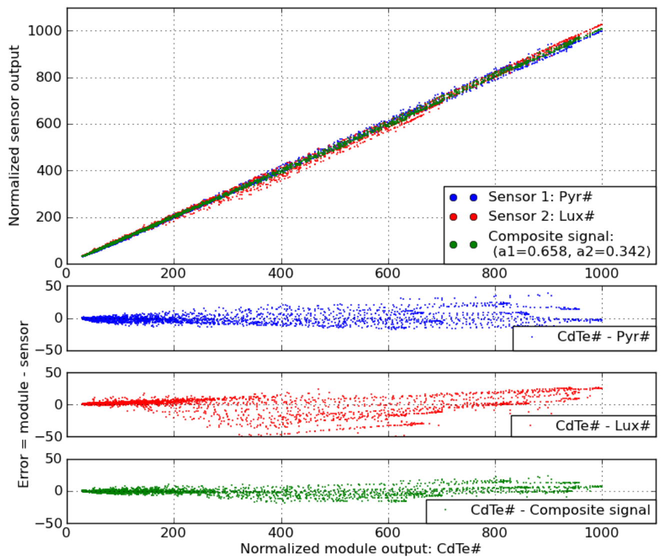

Fig. 2. Predicting the output of a CdTe module using a Pyranometer and Lux sensor. Sensor and module outputs are calculated from measured spectra; composite sensor output is a weighted sum of the calculated sensor outputs.

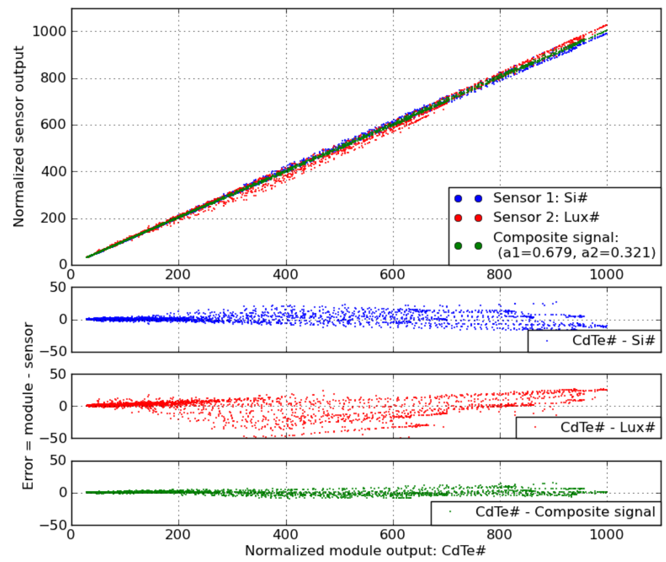

Fig. 3. Predicting the output of a CdTe module using an Si sensor and Lux sensor. Sensor and module outputs are calculated from measured spectra; composite sensor output is a weighted sum of the calculated sensor outputs.

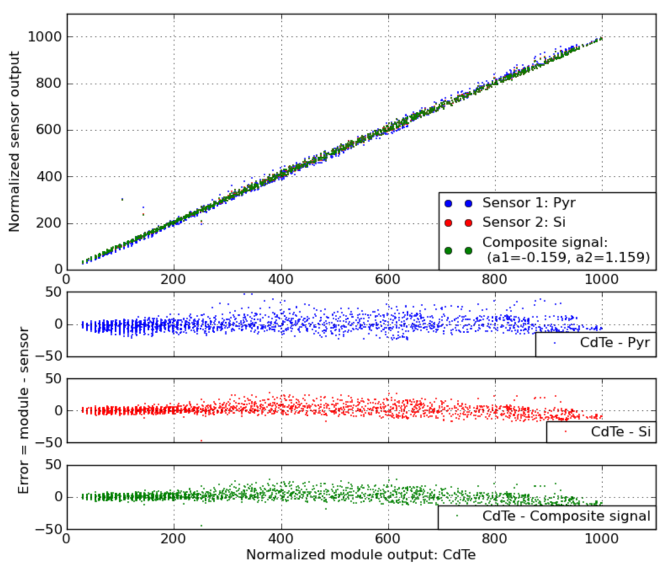

Fig. 4. Predicting the output of a CdTe module using a Pyranometer and Si sensor. Sensor and module outputs are cosine-corrected measurements; composite sensor output is a weighted sum of the measured sensor outputs.

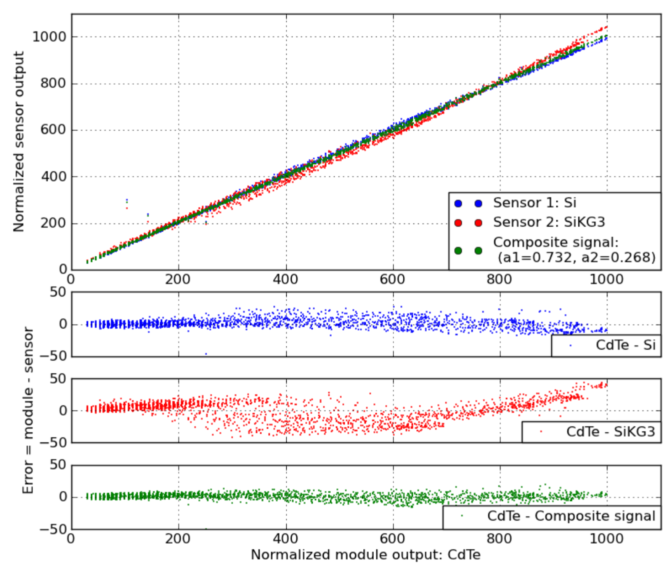

Fig. 5. Predicting the output of a CdTe module using a Si sensor and Si sensor with KG3 filter. Sensor and module outputs are cosine-corrected measurements; composite sensor output is a weighted sum of the measured sensor outputs.

Calibration requirements are not addressed in this paper, but have not been forgotten. Normalization of the data was a convenient form of relative calibration to minimize the mean bias errors. The values of the weighting parameters listed in the tables would of course change with a different calibration. A practical approach would be to calibrate the sensors at AM1.5, and subsequently redo the regression analysis to determine the new weighting parameters. When calibrated in this manner one could also recognize AM1.5 conditions simply by observing when the sensor signals are equal.

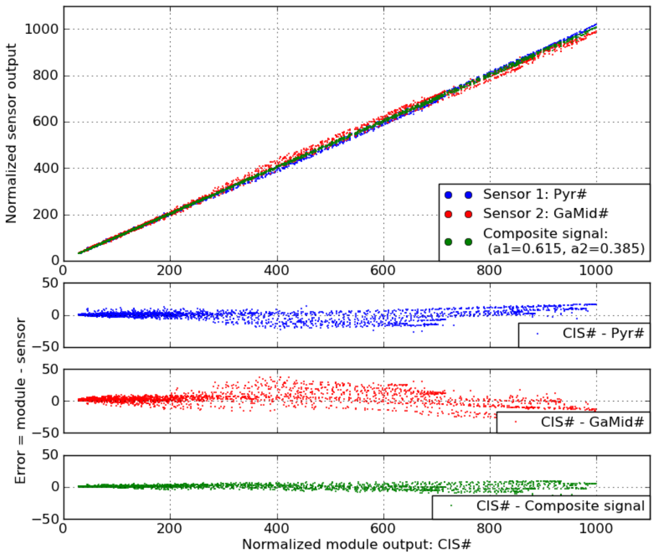

Fig. 6. Predicting the output of a CIS module using a Pyranometer and the middle junction of a triple-junction cell. Sensor and module outputs are calculated from measured spectra; composite sensor output is a weighted sum of the calculated sensor outputs.

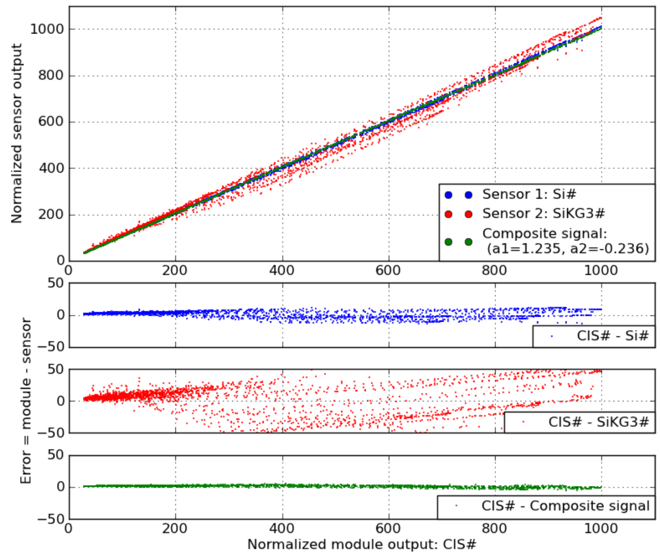

Fig. 7. Predicting the output of a CIS module using a Si sensor and Si sensor with KG3 filter . Sensor and module outputs are calculated from measured spectra; composite sensor output is a weighted sum of the calculated sensor outputs.

VII. Conclusions and Further Work

Our measurements and calculations have demonstrated that it is possible to substantially improve the performance monitoring of CdTe and CIS modules by pairing a standard pyranometer or silicon reference cell with a second spectrally selective irradiance sensor. Calculating a weighted average of the two sensor signals produces a composite signal that correlates much more closely than a single sensor with the output of the module type in question.

There was not a single best sensor combination, or a single sensor that stood out as a best second sensor. All three sensors sensitive at the lower wavelengths (Lux sensor, Si with KG3 filter and GaInP top junction) provide roughly similar benefits when used as a second sensor.

The dual-sensor approach offers important advantages over matched reference cells for monitoring thin film PV. First, the same pair of sensors can be used with different weighting parameters to serve different technologies. And second, the sensors can be made by independent parties using stable, proven materials—even for monitoring newly developed PV technologies with unique spectral characteristics. This ensures that the sensors do not exhibit the same potential weaknesses as the modules, which is a danger when using reference cells of the same technology.

A general observation arising from this work is that each sensor has its own unique imperfections. We will never have perfect sensors that are affordable, but imperfect sensors are much more useful when they are accurately characterized. We therefore encourage sensor manufacturers to publish detailed specifications of spectral response, cosine response, and temperature dependencies for products aimed at the photovoltaic market.

There are several aspects of this method that require further work before it can be broadly used. Cosine-error correction is the key to using very different styles of sensors together; however, it would be preferable to find or develop sensors that have similar or identical optics where the cosine-errors are small. The fact that the diffuse/direct irradiance ratio is required for this correction is a disadvantage, and it should be investigated whether a simple model-based determination of this ratio would be adequate for the cosine correction.

Based on our positive results we expect that this method will become very useful tool, both for monitoring thin film PV systems, and for quantifying and understanding the long-term gains or losses due to differences in PV spectral response.

Acknowledgement

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References

[1] N.H. Reich et al. “Performance ratio revisited: is PR > 90% realistic?” *Progress in Photovoltaics*, 2012.

[2] C.N. Jardine, T.R. Betts, R. Gottschalg, D.G. Infield, K. Lane, “Influence of spectral effects on the performance of multijunction amorphous silicon cells,” *Proc. Photovoltaics in Europe*, 2002.

[3] D. Dirnberger et al. “Simplifying measurements of spectral irradiance,” *Proc. EU-PVSEC*, Hamburg, Sept. 2011.