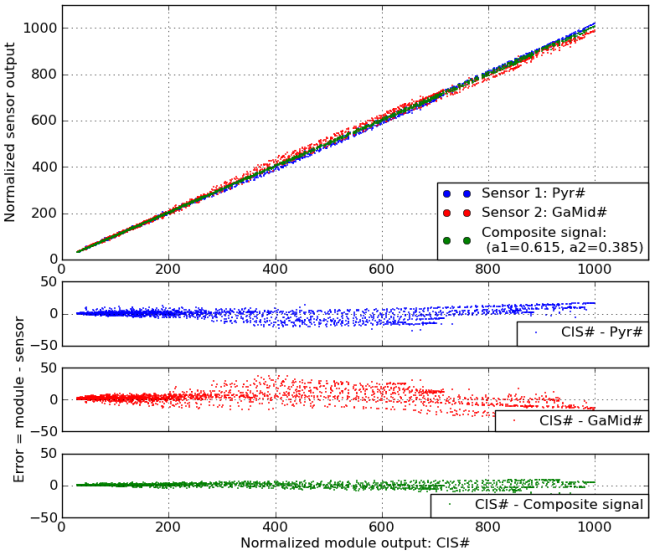

Fig. 6. Predicting the output of a CIS module using a Pyranometer and the middle junction of a triple-junction cell. Sensor and module outputs are calculated from measured spectra; composite sensor output is a weighted sum of the calculated sensor outputs.

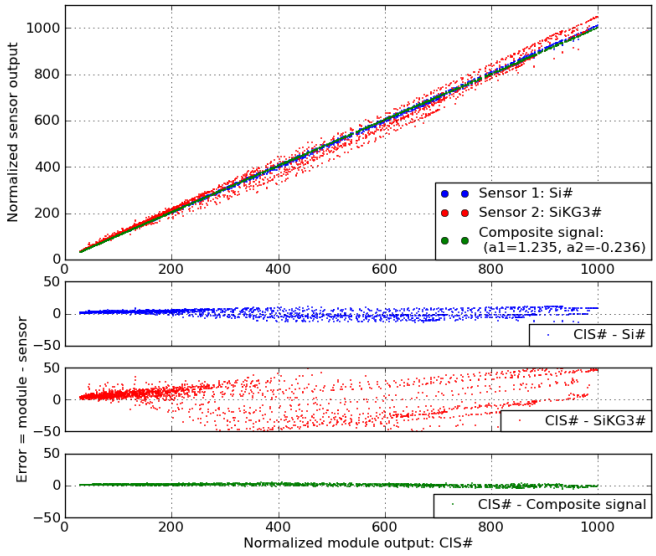

Fig. 7. Predicting the output of a CIS module using a Si sensor and Si sensor with KG3 filter . Sensor and module outputs are calculated from measured spectra; composite sensor output is a weighted sum of the calculated sensor outputs.

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.

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