Field Investigation of the Effect of Spectral Response upon Photovoltaic Energy Yields

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***Abstract*—The operating efficiencies of multi-junction photovoltaic cells are sensitive to changes in the spectral distribution of solar irradiance. To examine how this affects their performance in the field, two sets of triple-junction photovoltaic cells with different spectral responses are being characterised side-by-side outdoors. Initial analyses of the measurements have revealed seasonal differences between the performances of the cells that can be attributed to their spectral responses. This suggests that more long-term data will show how the choice of spectral response can impact the annual performance ratios for multi-junction photovoltaic systems.**

***Index Terms*—energy harvesting, energy measurement, III-V semiconductor materials, photovoltaic cells, solar energy, solar power generation.**

I. INTRODUCTION

Multi-junction photovoltaic (PV) cells continue to break laboratory conversion efficiency records. The latest devices incorporating four active junctions have demonstrated conversion efficiencies in excess of 46% [1]. Whilst the interest in using these high efficiency cells for photovoltaic electricity generation is understandably increasing, questions arise about the impacts of the increased spectral sensitivity of these cells upon their operating efficiencies in the field. Since cells of this type are typically manufactured for optimal performance under the standard AM1.5D (direct) spectrum, any deviation from this spectral condition will reduce the apparent operating efficiency of the cells.

Previous studies have predicted that the energy yield at a specific site can be increased by 'tuning' the spectral response of a triple-junction photovoltaic (PV) cell to better exploit the local spectral resource [2]–[4]. This work has shown that, when considered over a full year, the balance of currents generated in each junction can affect the performance ratio (kWh/kWp), and thereby the final cost calculations of a PV installation.

This paper presents the results to-date of an experiment that has been designed to gather field performance data to evaluate the effect of spectral sensitivity upon the energy yield of multi-junction cells.

II. METHODOLOGY

A. Approach

The aim behind the experimental design was to acquire data in a manner that would highlight the effect of spectral response. This required the simultaneous collection of data from two concentrator photovoltaic (CPV) systems operating under identical conditions, and of identical design with the exception of their spectral responses. A set of custom-made CPV modules was therefore designed and fabricated for this experiment, and mounted on a single dedicated solar tracker.

To isolate the effect of spectral response, two different triple-junction cell designs were selected with the primary requirement that they were physically identical yet exhibited different spectral responses. The first technology, cell 'Type A', incorporated a lattice matched structure, whilst cell 'Type B' utilised an upright metamorphic structure. The external quantum efficiencies (EQEs) for both cell types were measured in the laboratory and the values of the top and middle junctions of are shown in Fig 1. Type A cells have a narrower response range in both of these junctions compared to the type B cells. The cells were chosen to be as dimensionally similar as possible, as well as utilising similar bus-bar designs. For this reason, both cells were purchased from the same manufacturer, which stocked cells of similar physical aspect.

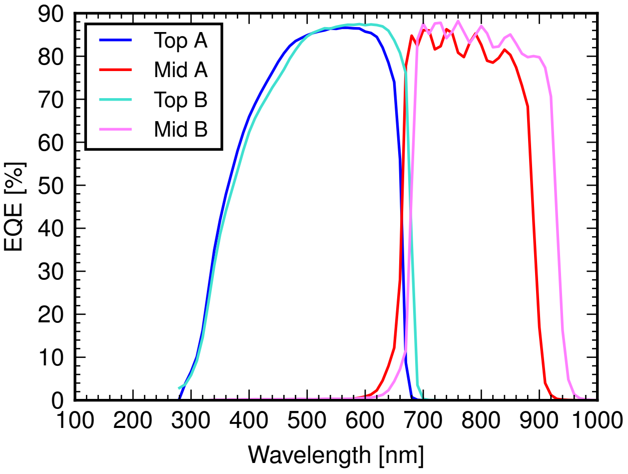

Fig. 1. External Quantum Efficiencies of the top and middle junctions measured for the two cell types used in this work. The type B cells exhibit a wider response range for both junctions.

From these cells, 8 identical CPV modules have been fabricated by the Fraunhofer Institute for Solar Energy Systems (ISE); 4 modules containing only type A cells (Mod AX), and 4 modules containing only type B (Mod BX). The modules are an all-glass design, and incorporate silione-on-glass (SOG) fresnel lenses, which have a good track record for durability in the field. This module design has shown reliable performance over many years of development, and was chosen for its track record of outdoor operation [5]. The modules are not hermetically sealed, but allow an air flow in and out of the enclosure through a filter. To avoid loss of data arising from condensation forming on the inside of the modules either after rain or overnight, an airflow system was used to pipe dry air into the modules. Although some condensation can occasionally still occur, this causes minimal loss of data.

Six triple-junction cells were wired in series inside each module. The cells were over-sized for the application, to reduce the possibility that manufacturing tolerances could influence the final performance. The modules thus have a low geometric concentration ratio of only 53 X, which reduces the effect of tracking errors or internal misalignments. The peak irradiance intensity at the centre of the cells is estimated to be around 2500 suns, which is tolerable for both cell types. It was also recognised that temperature changes in the SOG lenses can cause significant changes to the module efficiency, and oversizing the cells also reduces this effect.

B. Data Collection

Two modules of each type have been installed outdoors at the University of Cyprus' Photovoltaic Park in Nicosia, Cyprus, as shown in Fig. 2. This location was chosen due to its high annual direct normal irradiance (DNI), to provide as much data as possible over the test period. The modules were mounted on a Kipp & Zonen 2AP tracker, and aligned using a system of spring mounts. Alongside these modules were installed: a pyrheliometer for measuring broadband DNI; a pyranometer for recording global normal irradiance; temperature sensors for measuring back-of-module and ambient temperatures; and a collimating tube for collecting light for a spectroradiometer system. The spectroradiometer collects data at a resolution of 2 nm over the range 300 - 1650 nm with an acquisition time of several milliseconds [6].

The four outdoor test modules are currently being used to collect data field over a complete year. A custom current-voltage (IV) tracing system is being used to take sequential measurements of the IV characteristics of each module. The modules are kept at open-circuit conditions between scans. This is done to avoid potential differences in cell temperature arising due to the operating efficiencies of the different cell technologies. The IV curves provide information such as the open circuit voltage, short-circuit current, fill factor as well as the maximum power of the modules. Simultaneously, the ambient operating conditions of the modules are recorded, including spectrally-resolved direct normal irradiance measurements. The spectral data is collected in order to later analyse the output of the modules as a function of the spectral content of the solar irradiance.

Fig. 2. One of the completed test modules installed on the 2AP tracker.

The data acquisition system is programmed to take measurements at 5 minute intervals when the DNI exceeds 400 Wm^{-2}. Each measurement sweep requires approximately 10 seconds to complete. Field data has been collected since October 2014.

The remaining four modules are used as reference modules, and are kept indoors under controlled conditions. Two of the modules are kept at the Joint Research Center, and the other two are kept at the University of Cyprus' Photovoltaic Technology Laboratory. These modules are regularly tested outdoors and characterised at standard concentrator test conditions (SCTC) to provide a reference point for the operation of the outdoor modules. This information is used for the calculation of the module performance ratios, and also as a means to detect any signs of performance degradation.

III. RESULTS

A. Influence of Spectral Irradiance

To-date, the four test modules have been measured outdoors over the period from October 2014 until June 2015. During this period the outdoor spectroradiometer system has been measuring continuously, and has been calibrated on three separate occasions. To validate both the spectral irradiance and the module measurements, the measured spectrum has been convolved with the cell spectral response measurements to produce current generation values for the two module types. Figure 3 shows the variation of the short-circuit current output of all the test modules on a clear day in April 2015. Against these measurements, the simulated currents for the two different cell types have been plotted, assuming an optical efficiency of 87% for both module types. This analysis shows an excellent agreement between the measurements and simulations, confirming the correct operation of the spectroradiometer system as well as the module measurements.

The influence of the solar spectrum is also evident in the fill factor of the two modules types over the day, as plotted in Fig. 4. This plot shows a clear inflection point where the current generation in the top and middle junctions of the cells are balanced in each module. At either side of the inflection point either the top or middle junction is limiting the current,

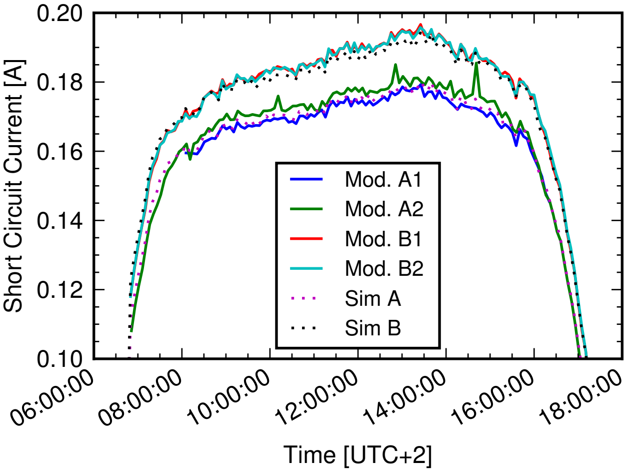

Fig. 3. Plot showing the change in short-circuit current of the four modules under test on 4 April 2015, alongside simulations of the output of the cells in both module types. The same optical efficiency, 86.8%, was used in each case.

and causes a corresponding increase in the device fill factor. This inflection point happens at different times depending on the spectral response of the cells, and has been accurately predicted by examining the simulated current outputs based on the spectral irradiance measurements.

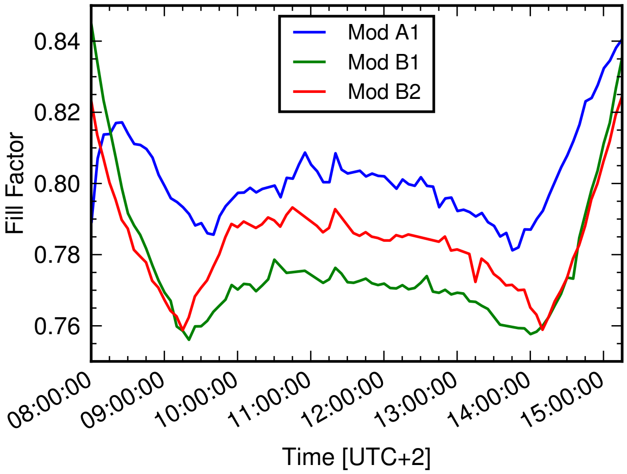

Fig. 4. Plots of the change in fill factor for the three modules under test on 23 December 2014. The fill factor shows a distinctive inflection where the change in limiting junction occurs. The different times at which this inflection occurs is a result of the varying spectral response of the cell technologies used.

B. CSOC Performance

As the objective of these measurements is to examine the relative, not absolute, performance of the modules, a benchmark measurement against which to compare the outdoor performance of each module type is needed. The performance efficiency of each module at concentrator standard operating conditions (CSOC) has been used for this purpose. CSOC conditions are defined in the standard IEC 62670-1 *Concentrator Photovoltaic (CPV) Performance Testing Standard Conditions* as a DNI irradiance of 900 Wm^{-2}, an ambient temperature of 20 ∘C, a wind speed of 2 ms^{-1} and a spectral irradiance distribution consistent with the the AM1.5D spectrum defined in IEC 90604-3.

The CSOC performance was determined according to the procedure given in the draft standard IEC 62670-3 *PV Performance Testing – Performance Measurements and Power Rating*. The data for the analysis was obtained by filtering the entire outdoor dataset for the CSOC conditions of DNI, ambient temperature, wind speed and spectral matching ratio (SMR1). The average values for maximum power and efficiency were then obtained from the remaining data. These results are summarised in Table I.

TABLE I
CSOC PERFORMANCE SUMMARY FOR THE FOUR TEST MODULES

Module	Module ID	Pmax [W]	Efficiency $\pm 1\sigma$ [%]
Mod A1	ISE122	2.504	28.98 ± 0.46
Mod A2	ISE123	2.439	28.23 ± 0.58
Mod B1	ISE126	2.557	29.59 ± 0.64
Mod B2	ISE127	2.608	30.02 ± 0.62

C. Performance Ratio Calculations

The performance ratio is commonly used as a way to quantify the real operating efficiency of a PV system in the field, relative to its rated efficiency. Whereas conventional flat-plate PV technologies are rated to standard test conditions (STC), in this procedure we calculate the performance ratio against the CSOC rating. This was done since the CSOC performance is easier to determine than the CSTC (concentrator standard test conditions) performance, and also because it provides a more immediate indication of the relative outdoor performance. The performance ratio PR was therefore calculated according to Equation 1, where η_{CSOC} is the module efficiency at CSOC conditions, $G_{\text{DNI}}(t)$ and $P_{mpp}(t)$ are the direct normal irradiance and maximum power of the module at moment t respectively, and A is the module area.

$$PR = \frac{\sum P_{mpp}(t)}{\sum \eta_{\text{CSOC}} G_{\text{DNI}}(t) A} \tag{1}$$

The performance ratio of each module was then determined over the entire measurement period from October 2014 to May 2015, and the mean PR of each module type was calculated. The final PR values are presented in Table II, and show close agreement between the different modules, with no difference discernible outside of the standard uncertainty of the measurements.

IV. Discussion and Analysis

The close match between the performance ratios of the two cell technologies presented in Table II suggests that the different spectral response of the two types does not affect the

TABLE II
PERFORMANCE RATIO FROM OCTOBER 2014 TO JUNE 2015

	Type A Module	Type B Module
Performance Ratio	0.977	0.980

energy yield per watt-peak installed. On the other hand, as the examination of the different fill factors in Fig. 4 has shown, there is a discernible difference in the daily performance of the different module types. Hence a closer examination of the dataset is required in order to explain the similarity in the final PR value.

The mean performance ratio of each module type was calculated for each month of measurements separately. The difference between the monthly PR of each type was then calculated by subtracting the Type A results from the Type B, and these differences are plotted in Fig. 5. From this graph, it can be seen that there are variations in the monthly performance ratios of the two modules. However, these differences average out over the full measurement period. This information indicates that data collected over the summer period at this location could introduce a significant difference in the PR values in Table II, and improve the apparent performance of the Type A cells.

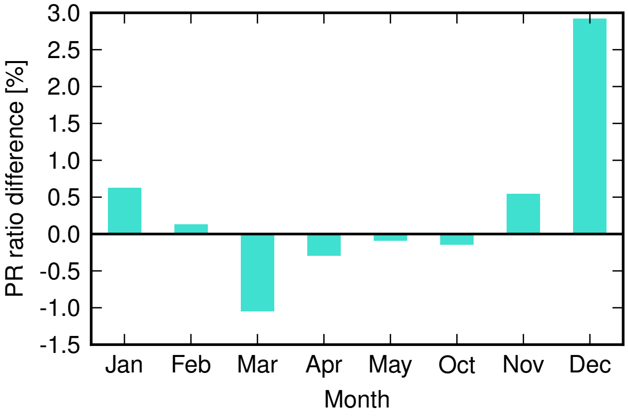

Fig. 5. Monthly difference in the mean performance ratios between the two module types. A positive difference indicates the Type B modules performed better, whilst a negative value indicates the Type A modules performed better.

Since care was taken in the design of the experiment to negate the effects of temperature, alignment, and optical efficiency, the prime candidate for the effects seen in Fig. 5 is the spectral distribution of the irradiance. Although temperature is likely to influence the performance ratio of these modules, the temperature coefficients supplied by the manufacturer indicate that the effect would account for a fraction of a percent.

To examine the possibility that the spectrum affected the apparent performance ratio, the spectral matching ratio (SMR) was calculated for the top and middle junctions of the Type A cells for each measurement instant. The SMR indicates the relative balance in carrier generation in the different junctions of a cell, and becomes unity when the balance is equal to that occurring under AM1.5D conditions. The most important SMR value is that between the top and middle junctions as these are almost always the current-limiting junctions. These SMR values were then averaged over each month of measurements, and the results are plotted in Fig. 6.

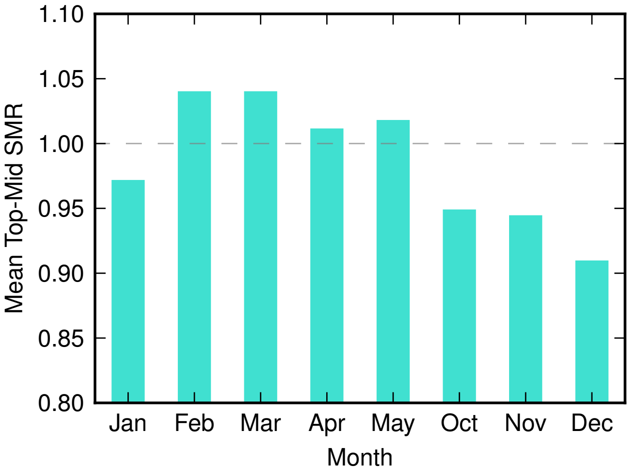

Fig. 6. Calculated monthly average top-middle junction SMR values for the period October 2014 to May 2015. A value of 1 signifies a current balance identical to that achieved under AM1.5D spectral conditions.

Fig. 6 shows that the the average spectra in the months from February to May contained a larger 'blue' wavelength component compared to the AM1.5D spectrum, and thus were more likely to see middle-junction current limitation within the cells. Comparing the results of Fig. 6 with the differences in performance ratio in Fig. 5 suggests a relationship exists between the average spectral balance and the relative performance ratios of the two cell types. Type A cells perform better with a more 'blue-rich' spectral resource, whereas the Type B cells perform better under more 'red-rich' spectra seen in the winter months. Due to the variations visible in the data at this point, it is pertinent to obtain further long-term data to assess whether this is a valid observation.

Notwithstanding the need for further data, the conclusion above, although tentative, is reasonable. The optimal performance of triple junction cells occurs when the current output from the individual junctions is balanced. In the Type A cells, this balance point is achieved under conditions containing more 'blue-rich' spectra compared to the Type B cells, as a consequence of the narrower response range of the top junction. Conversely, the Type B cells are operating further from their optimal current balance under the same blue-rich conditions and will therefore display a lower performance ratio. The situation is reversed under more 'red-rich' spectra.

V. CONCLUSIONS

The possibility of examining the influence of the spectral response of multi-junction PV cells upon energy yield is being investigated by comparing the output of two different cell types under identical field operating conditions. The initial results have identified no significant difference in their long-term performance ratios. Whilst some differences in performance ratio are seen at certain times of year, these tend to normalise over the long term. Moreover, it has not yet been conclusively demonstrated that the differences in performance ratio can be attributed to the change in spectral resource. While this finding brings into question the possibility of using spectral response tuning to improve energy yield, it shows that cell designers have flexibility in choosing their junction response ranges without incurring a performance penalty in the field. However, the data upon which this conclusion is based has not yet covered a complete year, and more data is required before a firm conclusion can be drawn.

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