Recommendations for new testing guidelines (D17)

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4. Summary

1. Introduction

D17 is a deliverable of Work Package 7 which targets the development of advanced testing and rating procedures over and above those included in the standard for CPV. The purpose of this is to obtain a greater understanding of the strengths and weaknesses of the current standard IEC 62108 and thus investigate whether there is a need to adopt such advanced procedures in future type approval specifications. In D17, we present some recommendations and guidelines on improved lab testing procedures for CPV modules, on the rating of CPV systems and the STC to be used for this purpose.

2. Recommendations for outdoor testing

2.1 Long-term CPV performance evaluation

For CPV modules, it is important to ensure the reliability of tracking, to design enclosures that can withstand over 20 years of outdoor exposure, to achieve adequate cooling of the PV cells, and to ensure that optical performance does not degrade significantly over time. During this project we have obtained important long-term field experience on the evaluation of CPV modules by studying a medium concentration CPV system.

The testing procedure in the PV Technology Laboratory, UCY involved current-voltage (I-V) characterizations of modules performed every 1-5 minutes and recording key performance
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indicators alongside environmental and irradiance data. The performance of the system was monitored in real conditions for three years. Only occasional cleaning was performed, which was done intentionally to examine the impact of soiling on the system output. The CPV system was left open-circuited between measurements. The power output of the system was measured by extracting the maximum power point (mpp) of each I-V characteristic, which avoided the need to account for the effect of an mpp tracker. This approach assumes that the effect of keeping the system at open-circuit, rather than at mpp between characterizations, is negligible.

Figure 1: Cumulative energy yield plotted against the cumulative DNI resource showing a drop in output over a specific period during which the tracker malfunctioned.

The long-term testing of a CPV module can provide valuable information on various key parameters affecting CPV outdoor performance including performance ratio, tracker performance, operating temperatures and optical efficiency. The performance ratio (PR) was used as a good indicator of the long-term operating efficiency of the system. This was calculated by dividing the long-term operating efficiency by the system efficiency at standard test conditions. The long-term efficiency was calculated by dividing the cumulative energy generation by the cumulative DNI resource over the test period. The results of the PR analysis apart from illustrating the general behaviour of the system, also showed any drops in output over a specific period which translated in any tracking malfunctioning periods (Fig. 1). Periods when the system was left unclean were also reflected in the PR results obtained.

The long-term output monitoring of CPV systems also enables the observation of problems with the tracker performance. Minor failures were observed during the monitoring period, mainly of mechanical nature. The first was when the mounting bracket of the drive chain failed resulting in an offset in the azimuth tracking at some parts of the day. This could be due to the extended exposure to the elements as well as working stresses on the tracker. With this particular fault,
the system is able to operate at maximum for some parts of the day, only failing to track correctly when the faulty section of the bearing is loaded. This fault was remedied by repairing the mounting bracket. The second fault was a gradual degradation of the transparent material covering the tracking sensors; this resulted in a difference in irradiance level received by each sensor and gradually producing an offset in the elevation tracking which was manifested in a low optical efficiency that dropped over the course of the day. This fault was corrected through a combination of cleaning the sensor cover, performing software compensation and adjusting the sensitivity of each sensor. In order to identify tracking faults, the short-circuit current from the collector, which is an indicator of the output of the collector, can be compared with the output expected by the modeled acceptance of the unit. In this way, mechanical as well as sensor soiling tracking faults were identified (see Fig. 2).

Figure 2: Two types of observed tracking faults: (left) mechanical and (right) sensor cover soiling. The calculated acceptance curve shows the anticipated output profile if light was accepted by the system over the day without interference. The peaks on either side of the graph result from off axis light reflected from the side walls onto the cells.

Concerning the investigation of operating cell temperatures, it was found from our studies that a temperature difference of approximately 10 °C is present between the cell and the back of the module, with no considerable thermal lag under varying conditions. Overall, the recommendation for investigating the operating temperatures based on the experience generated is the following: Cell temperatures are determined using back-of module temperature measurements. To convert these measurements to cell temperatures, a 1-diode model of the PV system to predict I-V curves under certain temperatures is used. Using the data collected over the period of some years, a model to relate the environmental and irradiance conditions to the cell temperature is produced. In order to account for the effects of tracking error and soiling on the irradiance levels on the cell surface, the model needs to be developed to relate cell temperature above ambient to wind speed and short-circuit current, the latter being a reliable indicator of the total irradiance falling on the cell surface. The results that the operating cell temperatures measured are similar to the nominal operating cell temperatures (NOCT) of flat-plate PV modules. This is a worthnoted result which
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suggests that a well-designed heat sinking system can achieve the NOCT typical of flat-plate systems without the need for active cooling.

With regards to the **optical efficiency losses** from a CPV system, the recommendations generated from our studies are the following:

(i) It is important to properly temper lenses in production to prepare them for large variations in operating temperature, although fractures that can occur in PMMA lenses are not a major source of energy loss in their own right.

(ii) A regular cleaning regime is necessary in countries with warm dry summers as the effect of soiling on the performance of CPV systems is a key factor that can reduce system energy yields. This can actually affect both tracking accuracy and optical efficiencies to reduce outputs by over 30%.

2.2 Measurement of CPV module energy yield

The present draft of the IEC standard 63670-3, which deals with the measurement of CPV module power under normal operating conditions, does not require a module to be held at a particular voltage bias condition between measurements. In order to establish the extent to which the operating bias voltage between measurements affects the operating temperature of cells within and therefore the measured system power output, CPV modules were tested under 2 key bias cases: Voc and mpp. In particular, the chosen approach looked at the relationship of cell operating temperatures and bias voltage condition, the associated power losses of the module, and how this would influence the estimated energy yield of the system. The I-V characteristics of the modules were accumulated whilst being held under both mpp and at Voc bias between measurements. Integrated temperature sensors provided an indication of the actual junction temperature of the cells under each bias condition.

This work suggested that for some CPV modules, there is a measurable change in cell temperature when the module is operated in Voc or mpp bias conditions. The effects are strongest in modules with high-efficiency cells as these will run cooler since they convert more incident energy to electrical power. This suggests also that this effect will become more evident as modules become more efficient in the future. It was shown that the choice of bias condition could alter cell operating temperatures by 3-4 °C in case of high-efficiency cells, equating to an average relative power loss of about 2% when operating in the hotter condition. Whilst this effect can be seen in I-V characterizations, it can be corrected for with good cell temperature measurements, and is effectively negligible in longer term energy yield measurements.

These factors together support the current assertion within the draft IEC 63670-3 standard that at present mpp biasing between I-V measurements is not necessary for the calculation of power output of CPV modules at normally operating cell temperatures.

2.3 Tracking accuracy assessment for CPV systems
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There is a strong requirement for a means of assessing the pointing accuracy of solar tracking equipment for the determination of CPV module performance. This work was carried to gain an understanding and determine the tracking accuracy of a CPV system. A commercially-available advanced positional accuracy monitor was used for evaluating the tracking error of a system. The practical application of these accuracy monitors relies on the correct installation and alignment with the tracking systems under test, and by the same token, the alignment of the modules with the same tracking frame. A Trac-Stat SL1 accuracy monitor has been used in the determination of pointing accuracy and has been integrated into the outdoor CPV module test facility at the PV Technology laboratories in UCY.

A dynamic system model was developed to characterize the performance of the CPV system that would indicate the output power of the unit, given a complete set of environmental conditions, including wind speed and direction, ambient temperature, humidity, as well as total irradiance levels (DNI and diffuse irradiance). The latter term was modelled as a function of the tracking accuracy. All environmental parameters relevant to the tracker model were logged instantaneously alongside the tracking accuracy. The data sets were used to develop and validate the model. The tracking accuracy was defined as one standard deviation of the probability distribution with which the tracking system could maintain the tracking sensor pointing directly at the sun. The most convenient way in which to present the tracking accuracy data is in the form of histograms, which can quickly convey the frequency and distribution of error readings. The data shown in figures 3 and 4 are typical examples of raw data for azimuth and elevation tracking error, and figure 5 is the corresponding total tracking error magnitude.

![Figure 3: Azimuth error data for the system under test, showing a negative skew.](image-url)
Figure 4: Elevation pointing error for one typical day, showing a relatively normal distribution about -0.07°.

Figure 5: Total pointing error calculated from the azimuth and elevation errors.

The results from this work indicated that the tracking system performed with a tracking error of less than ±0.05° at one standard deviation. The offset present to both azimuth and elevation data was quantified by comparing the calculated mean and median values of the azimuth and elevation data with the mean and median values of the total error. It was found that the most consistent values for the offsets were determined by considering the median values of the data sets as this value minimises the effects of outliers in the data. The data gathered was compared against the corresponding environmental conditions. There is a clear indication that at low DNI conditions (<200 W/m²) there is greater scatter in the error data. Similarly the tracker error is being compared against wind speeds and direction, but as of yet not enough data has been collected to draw a clear relationship between these parameters and tracker error.

Overall, the tracker accuracy assessment demonstrated the value of a high-resolution tracker accuracy monitor in the evaluation of tracker performance for CPV. Further analysis of data sets is expected to yield insights into the performance of particular tracking systems in relation to environmental conditions that would otherwise be very difficult to quantify directly. More widespread deployment of such monitoring devices is recommended as a useful tool to validate CPV performance measurements.
3. Recommendations for indoor testing

Multi-junction solar cells are typically not accessible separately (unlike single junctions) and thus the EQE measurements of multi-junctions present additional challenges compared to the measurement procedure for single junction devices. Correction of the current-voltage (I-V) parameters to Standard Test Conditions (STC) requires knowledge of EQE and spectral mismatch calculations. This work aimed to contribute to the improvement of multi-junction device characterization by reporting the effects of low and high shunt resistance on EQE under various voltage and light bias conditions. Furthermore, highlights the significance of dark EQE measurements of triple junction devices to indicate the shunt resistance values of each junction.

Dark EQE is a useful metric for extracting the impact of the shunt resistance on the EQE measurements and can be observed when we applied no light during EQE measurements of the triple junction device. The presence of low shunt resistance in the junction creates measurement artifacts that affect the EQE measurements of the photovoltaic device. Consequently, knowledge of the shunt resistance of the junctions can be used to predict the problems that will arise during the measurement of the EQE of the multi-junction device.

![Figure 6: External Quantum Efficiency of the GaInP/GaInAs junctions of a triple junction device at ideal light bias conditions (0.45 mA/cm²) for each junction and the corresponding Dark EQE of the device.](image)

Dark EQE measurements, as shown in Figure 6, resemble the case of low shunt resistance in the middle and bottom junction: the dark EQE of the device is a consequence of current leakage through GaInAs and Ge, giving rise to an increased EQE in the wavelength region of the top junction due to low shunt resistance of the middle and bottom junction respectively. The shunt resistance of the top junction is much higher than that of the middle one, as inferred by the very small EQE signal observed in the response region of the middle and bottom junction in the dark
measurements. Therefore it is expected to have more measurement artifacts during the EQE of the middle junction.

Then EQE measurements of the top and middle junction were investigated at different light and voltage conditions. Initially the multi-junction device was tested under varying voltage bias conditions and fixed, high intensity light bias conditions. We assume that high intensity light bias conditions correspond to light bias intensity that produces a photocurrent higher than 1.50 mA/cm\(^2\) in the device. Above this light condition coupling effects and underestimation of the EQE signal are present. High-intensity light bias conditions may be expected to reduce the impact of the low shunt resistance and eliminate the measurement artifact term and thus the reduction of the EQE signal. The EQE curves were investigated in a broad range of voltage bias values as seen in Figure 7 for both (a) middle and (b) top junctions.

Figure 7: Voltage bias dependence of the EQE in both (a) middle GaInAs and (b) top GaInP junction under high intensity light conditions. High intensity light bias conditions correspond to photocurrents of 4.50 mA/cm\(^2\) for middle GaInAs and 2.17 mA/cm\(^2\) for the top GaInP junction.

Under those conditions the variations of the EQE signal due to voltage are negligible as shown in Figure 7. Thus under high intensity light bias conditions the shunt resistance effect is almost irrelevant and voltage bias does not strongly affect the measurements. However, those light
conditions are not ideal for measuring EQE curves since coupling effects are present. Coupling effects are present as underestimation of the EQE spectrum of the middle junction (the signal is roughly 10% lower compared to ideal conditions). Therefore it seems that strong light bias conditions eliminate the impact of bias but introduce the problem of coupling effects.

Then the effect of voltage bias under low intensity light bias conditions was investigated by performing EQE measurements on both GaInP/GaInAs junctions. Low intensity light bias conditions correspond to light bias intensity that produces photocurrent of 0.39 mA/cm². Under these conditions the effect of the voltage is expected to determine the EQE especially for low shunt junctions. For the top GaInP junction, voltage bias effects are negligible as shown in the case of high intensity light conditions (Figure 7(b)). However in the case of the middle GaInAs junction, voltage biasing has an important effect under low-intensity light bias conditions.

![Figure 8](image.png)

**Figure 8: Effect of voltage bias on middle GaInAs junction under low intensity light conditions. Low intensity light bias conditions correspond to generated photocurrent of 0.39 mA/cm².**

As shown in Figure 8 overestimation of the signal outside the area of response (e.g. at 950 nm) and underestimation within the region of response (e.g. at 800 nm) are artifacts due to shunts which actually increase in severity under decreased bias light. EQE values are lower (≈0.85) than in the ideal case shown in Figure 1 because of the inability of the bias light to cause current limitation of the junction of interest. The combination of very low shunt resistance of a junction with suboptimal lighting conditions gives rise to a very high measurement artifact term with severe effects on the EQE signal.

**Conclusions**

Results have shown that the voltage bias applied to the multi-junction cell has a strong effect only in the cases when the junctions have low shunt resistance. In the case of a junction with high shunt resistance, the voltage bias does not have a crucial role even at high or low intensity light conditions, so that could be neglected in the experimental practice. Thus the most important
factor to consider in order to reduce measurement artifacts below measurement uncertainties in the high shunt resistance case is the bias light intensity.

Our measurements showed that a light bias intensity that generates a photocurrent of roughly 0.45 mA/cm\(^2\) is the minimum light intensity required to produce good EQE measurements in our samples when the effect of the shunts is not of major influence. We have found that light bias conditions that produce photocurrents between 0.45 mA/cm\(^2\) and 1.50 mA/cm\(^2\) are sufficient enough for EQE testing of the cells under investigation. Measurements of EQE at lower or higher light bias conditions as shown above result in incorrect EQE data due to non-sufficient light bias and observation of coupling effects respectively.

4. **Summary**

In this report we present improved lab testing procedures on CPV modules and cells and recommendations on the rating of CPV systems and the STC to be used. Outdoor and indoor procedures and results are described which involve the subjects of long-term CPV system evaluation, including testing the tracker performance and accuracy, the optical efficiency losses and energy yield measurements, as well as testing the effect of shunt resistance on the EQE measurements of multi-junction cells under various voltage and light bias conditions.