Outdoor degradation of CdTe modules at open circuit and at maximum power point

K. Sinapis[1], G. Papageorgiou[2], K. Durose[2], M. van den Donker[1], W. Folkerts[1]

[1]Solar Energy Application Centre, Eindhoven, The Netherlands

[2]Stephenson Institute for Renewable Energy, Liverpool University, Liverpool, United Kingdom

Abstract — **A combination of outdoor exposure and laboratory measurements were utilized to characterize the differences in degradation of commercial CdTe modules in two operating modes. The degradation mechanism was observed on an array of 8 CdTe modules operated outdoors in open-circuit conditions. In contrast, a similar array of 8 grid connected PV panels operated at the maximum power point did not show any degradation over the same period of time. Of the degraded panels, V_{oc} and *FF* degraded 6% and 7% respectively. Electro-luminescence imaging showed large dark areas in the degraded modules. Spectral response measurements showed enhanced response at blue wavelengths but significantly reduced response at red and near infrared wavelengths. Results suggest that degradation studies at representative field conditions are equally important as the standard accelerated ageing methods and should be taken into consideration.**

Index terms — **CdTe modules, degradation, BIPV, reliability, EQE, EL**

I. Introduction

Solar modules are expected to provide a steady and reliable power output for at least 25 years. Reliability issues have to be identified and solved in an early stage. A key factor is the estimation of module lifetime in the field, thus various standards have been developed based on key stress factors [1] which can simulate, accelerate and reproduce performance degradation mechanisms.

With CdTe being one of the leading thin film module technologies, its degradation has been extensively studied and documented in the literature [2–5]. However, the underlying mechanisms are still under discussion. In most of the cases, the decrease in performance is attributed to deterioration of the back contact and/or junction quality. Common factors that lead to such issues include humidity [3], which can lead to formation of back-contact barriers, and diffusion of impurities from the back contact [4].

In this paper we present outdoor field results depicting different degradation trends of commercial CdTe solar cells at open-circuit and maximum power point (MPP) conditions, with the former demonstrating strong and fast ageing phenomena. Advanced laboratory characterization measurements will be presented to provide further insight in the degradation mechanism.

II. Methodology

For this work, an outdoor building integrated PV field test has been set up in Eindhoven, The Netherlands. 24 commercially available CdTe modules were used for the field test. 16 of the 24 modules were used in the 'DC test'. These modules were held at open circuit and tested with *I-V* tracing equipment (EKO instruments MP-160) acquiring a full *I-V* curve of 256 points every minute. 8 of the 24 modules were used in the 'AC test'. These modules were connected to two micro inverters from Power One (MICRO 0.3HV). The energy output of the AC system was monitored through a kWh meter from UPP Energy. The module temperatures were monitored by type T thermocouples. Irradiance was measured with a secondary standard pyranometer (EKO instruments MS-802). Data was logged and saved every minute for all inputs simultaneously.

Field test monitoring went live in May 2014 and were concluded in mid-October 2014. During this time the comprehensive data allowed for a detailed comparison between the two systems. After field exposure, the PV panels were dismounted and electroluminescence (EL) imaging was performed.

Finally, several small area samples from the degraded modules were prepared for further laboratory measurements. The small area samples were obtained by cutting the modules using a diamond wheel into 25 mm × 25 mm samples. These samples were annealed for short time periods using a hot plate at around 100°C so as to remove the backside glass and uncover the back contacts. Subsequently, 5 x 5mm^2 "active" regions were defined and the rest of the CdTe and CdS film was scraped off and etched with diluted HCl respectively. The study employed two groups of small area samples:

- DX.X - Samples extracted from the degraded modules, from a degraded region as judged by EL imaging.
- RX.X Reference samples from a non-degraded module

EQE, *C-V* and *J-V* measurements were conducted on these small area samples.

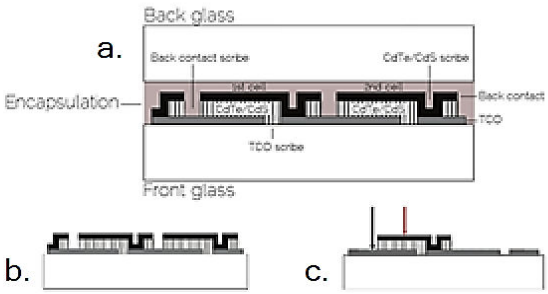

Fig. 1. Typical CdTe/CdS module: a) the configuration, b) with backside glass and encapsulation removed and, c) etched and contacted for laboratory investigations.

Fig. 2. The modules on the left hand side operate under MPP and were connected to micro inverters and power meter (‘AC test’) while the central and right hand modules were connected to an IV tracer (‘DC test’).

III. Results - Discussion on Module Level

The average degradation of the CdTe modules under open circuit conditions after outdoor exposure of 650 kWh/m^2 is shown in Table I.

TABLE I.
Calculated V_{OC}, I_{SC}, FF, P_{MAX} at Standard Test Conditions (STC) Before and After Outdoor Exposure

Cumulative irradiance	0	650kWh/m^2	
V_{oc} (V)	59.2	55.7	~6%
I_{sc} (A)	4	3.95	<2%
FF	0.62	0.58	~7%
P_{max} (W)	145.2	127.8	~12%

The performance ratio (PR) [6] defined in the equation below was used to compare the power degradation rate between solar modules operating at open circuit and modules at MPP. PR takes into account the total integrated power output of the modules $\Sigma P_{\text{measured}}$ (either DC or AC method), the total summed irradiance in the plane of the array, ΣG_{POA}, and both the irradiance and power output under standard conditions, P_{STC} and G_{STC}.

In fig. 3 the difference of the PR_{AC} and PR_{DC} is shown as a function of time during the trial. Unfortunately, the monitoring of the AC system started at a later stage than the DC system and for this reason the difference has been fitted and extrapolated back in time to estimate the PR differences starting from the 28th March when both the systems were installed. The initial difference of almost -5% is as expected taking into account the inverter and cabling losses of the AC system. By the end of May almost 5% of power degradation can already be observed for the open circuit modules of the DC system. The difference seems to stabilize around mid-August and continue almost unchanged until the end of field exposure.

$$Performance\ Ratio = \frac{\sum_{t_0}^{t_{end}} P_{measured}}{P_{STC}} \frac{G_{STC}}{\sum_{t_0}^{t_{end}} G_{POA}} \quad (1)$$

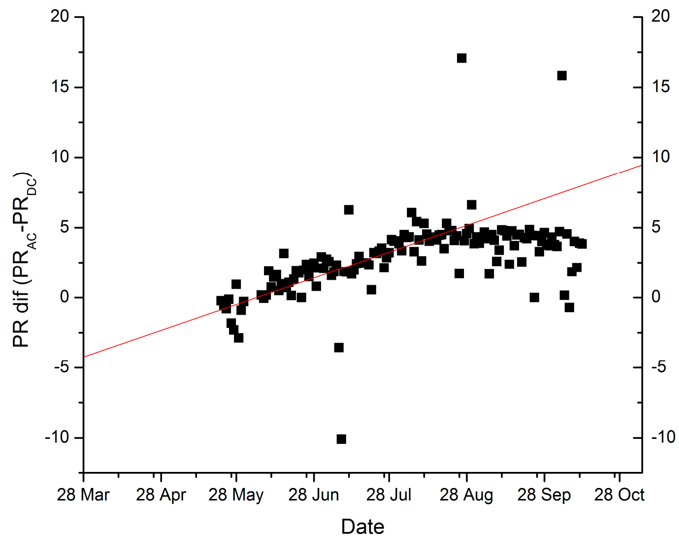

Fig. 3. Performance ratio difference of the AC (MPP modules) and DC (V_{oc} modules) vs field test date.

The performance degradation was further investigated by analyzing the I-V data from the DC field test which was operated in open circuit. Data with plane of array irradiance close to STC conditions was filtered (990-1010 W/m^2) and corrected for 25°C reference temperature with coefficients provided by the manufacturer’s spec sheet. From fig. 4 an average 12% degradation of P_{MPP} can be seen from the beginning of outdoor exposure on March until end of October 2014. The degradation of P_{MPP} can be primarily attributed to the degradation of Voc and FF (6 and 7% respectively). P_{MPP} degradation seems to stabilize after approximately 450 kWh/m^2 of irradiance. It is important to mention that the degradation of the three primary parameters (Voc, FF and P_{MPP}) of the solar module started immediately after outdoor exposure while Isc data shows small variations from month to month due to the irradiance sensitivity of Isc. A very small degradation of Isc of less than 2% can be observed for the whole period of outdoor exposure which falls in the measurement uncertainty of the equipment and no clear

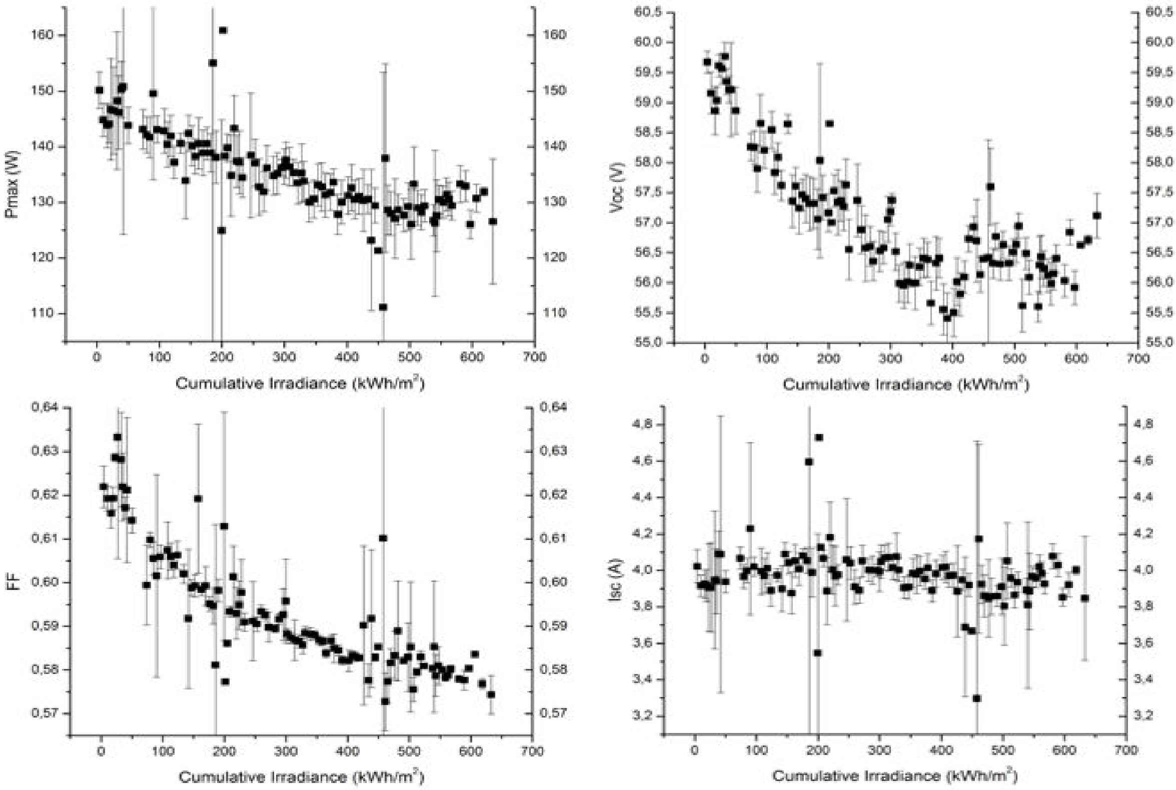

Fig. 4. Changes in the measured values from the CdTe modules in the 'DC-test' as a function of cumulative irradiance

correlation can be made. Similar results are supported by previous work [7].

To gain more insight into the observed degradation between the modules operating in open circuit and MPP, electroluminescence imaging was utilized. In fig. 5 an EL image of a non-degraded reference and a degraded module from the DC field test are shown. In the non-degraded module local shunts and scribing failures can be seen while at the degraded module (Fig. 5-right) a large area of the module's surface seems severely affected. As described in literature [8], damage to the TCO layer interrupts current flow and causes dark regions in the EL image. Similar results were observed for all the modules operating at *Voc*. Therefore, TCO damage is proposed as a degradation mechanism.

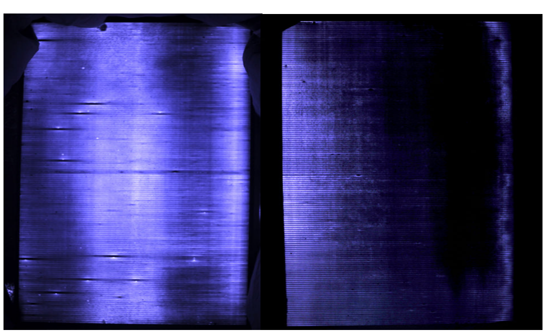

Fig. 5. Electroluminescence pictures from a non-degraded (left) and a degraded (right) degraded CdTe solar module.

IV. RESULTS-DISCUSSION ON CELL LEVEL

Fig. 6 shows representative *EQE* measurements from the degraded (D1.1, D1.2) and reference (R1.1, R1.2) samples. In order to evaluate these results, the main features of a typical *EQE* of a CdTe/CdS solar cell are analysed, these being:

- Region 1 (<500 nm): CdS and high resistivity transparent (HRT) layers
- Region 2 (500-550 nm): CdS/CdTe intermixing
- Region 3 (550-850 nm): CdTe

Comparison of the D1.X and R1.X *EQE*s shows an average efficiency gain of ~10% in the above-gap region of the CdS and a similar ~10% loss in the CdTe region for the D1.X samples. The two effects may be counterbalancing, but the losses in the CdTe region are more important taking in consideration that carriers generated in the CdS layer typically do not contribute to the photocurrent. (The carrier losses in the CdS layer are related to the fact that the depletion region exists almost entirely in the CdTe layer). Evaluation of the intermixing region shows a more gradual cut-off for the degraded cells. Such behaviour can be linked to a less abrupt junction and higher intermixing between the CdTe and CdS with the inter-diffusion affecting the band gap energies. Although these measurements depict a trend demonstrating changes in the junction quality and CdS region, they should be treated with caution: non uniformity of the individual layers across the whole module is not assured and, furthermore, such effects could be the product of the delamination process.

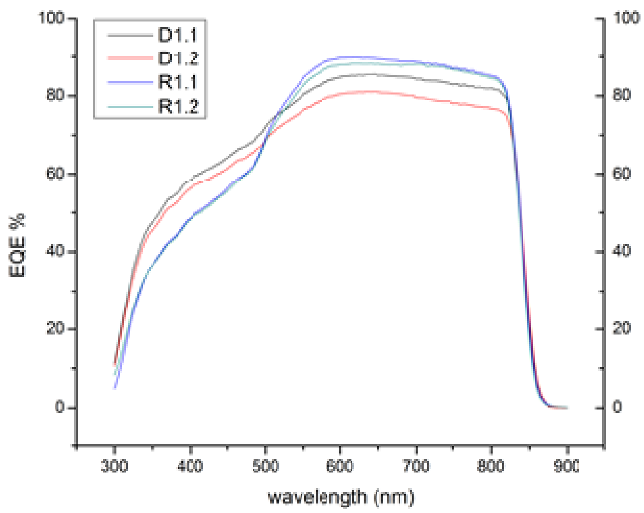

Fig. 4. *EQE* measurements from cells of the degraded outdoor exposed modules (D1.1, D1.2) and from the reference module that was stored in the dark (R1.1, R1.2).

To have a better understanding of the samples' quality, *C-V* measurements in the dark were conducted. The carrier densities of the samples were calculated from:

$$N = \frac{2}{q\varepsilon A^2 \left| \frac{d}{dV}\left(\frac{1}{C^2}\right) \right|}, \quad (2)$$

Where q is the elementary charge, ε is the permittivity, *A* is the cross-sectional area of the junction and $d(1/C^2)/dV$ is calculated using the slope of the respective plot.

TABLE II.
AVERAGE CALCULATED VALUES OF DEPLETION REGION *W*, AND CARRIER CONCENTRATION *N*

	Degraded	Reference
Avg. *w* (μm)	7.15	2.02
Avg. *N* (carriers/cm^3)	4.6 E+14	9.6 E+14

Additionally, the depletion area width was calculated from

$$w = \frac{\varepsilon A}{C}, \quad (3)$$

As shown in table II, the average doping concentrations *N* for the degraded samples are slightly lower than those of the reference samples. However, this difference falls within the measurement reproducibility and cannot be considered significant. The depletion area width *w* did show significantly higher values for the degraded samples. This expansion of the depletion region suggests that the collection width has increased but since actual collection is reduced, it is likely that the field is weaker too and that recombination is favoured. This broadening of the charge-free region could be due to diffusion of impurities or differences in the CdTe/CdS intermixing layer, evidence of which is demonstrated in the *EQE* characterisation as well.

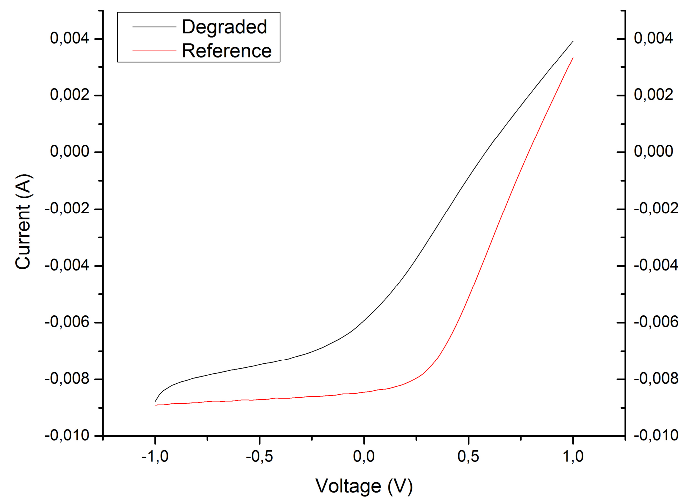

Fig. 5 *I-V* curve calculated from the cells of the degraded and reference module

Similar trends are observed in fig 7 for the *I-V* curves of representative sample groups of the degraded and reference cells. Changes in the series and shunt resistance with a direct impact in *FF* can be seen. Evidence of V_{OC} reduction is also present on the cell level measurements however, due to the voltage contribution of all cells in a module a wider sample set is needed to confirm the above conclusion. Additionally, non uniformity in the active layers could cause variations in I_{SC} measurements from the samples.

A wider selection of sample sets and further measurements such as EBIC and SIMS could reveal further information about the quality of the cell structure.

V. CONCLUSION

We uncovered a very strong and fast degradation mechanism in commercially available CdTe modules. The degradation took place during 650 kWh/m^2 of outdoor light exposure under open-circuit conditions. The power degradation of the modules was 12%. V_{oc} and *FF* degraded 6% and 7% respectively while I_{sc} seemed to be less affected. Modules that were grid-connected and operated at their maximum power point did not show this fast and strong degradation. This suggests that the degradation mechanisms occurring while exposed to irradiance at MPP and open circuit proceed at different rates and may be physically different.

EL, *EQE*, *C-V* and *J-V* measurements suggest degradation affects the CdTe/CdS intermixing, CdS and TCO layer. However, possible non-uniformity of the respective layers across the module or post-degradation effects caused by the delamination process may be factors that can affect the cell level results. Nevertheless, the implications of the overall degradation results make us believe that degradation mechanisms should be studied under field representative conditions at MPP although open circuit conditions might act as an acceleration factor.

Based on the experimental results, some practical advice can be given. For commercial use, it is suggested that installation and commissioning of CdTe modules in the field should be performed as soon as possible in order to avoid degradation from light exposure at open circuit. For R&D field tests and performance comparisons, it is suggested to use dedicated IV tracers that operate the module in MPP using a load during the measurement intervals.

ACKNOWLEDGMENTS

The authors would like to thank David Martinez Biro for performing the EL measurements. This work has been supported by the Netherlands Enterprise Agency (RVO) under TKIZ01013.

REFERENCES

[1] IEC 61426 2008 2nd Edition.

[2] K. D. Dobson, I. Visoly-Fisher, G. Hodes, and D. Cahen, “Stability of CdTe/CdS thin-film solar cells,” Sol. Energy Mater. Sol. Cells, vol. 62, no. 3, pp. 295–325, May 2000.

[3] V. P. Singh, O. M. Erickson, and J. H. Chao, “Analysis of contact degradation at the CdTe-electrode interface in thin film CdTe-CdS solar cells,” J. Appl. Phys., vol. 78, no. 7, p. 4538, Oct. 1995.

[4] B. T. Ahn, J. H. Yun, E. S. Cha, and K. C. Park, “Understanding the junction degradation mechanism in CdS/CdTe solar cells using a Cd-deficient CdTe layer,” Curr. Appl. Phys., vol. 12, no. 1, pp. 174–178, Jan. 2012.

[5] I. Visoly-Fisher, K. D. Dobson, J. Nair, E. Bezalel, G. Hodes, and D. Cahen, “Factors Affecting the Stability of CdTe/CdS Solar Cells Deduced from Stress Tests at Elevated Temperature,” Adv. Funct. Mater., vol. 13, no. 4, pp. 289–299, Apr. 2003.

[6] N. H. Reich, B. Mueller, A. Armbruster, W. G. J. H. M. van Sark, K. Kiefer, and C. Reise, “Performance ratio revisited: is PR□>□90% realistic?,” Prog. Photovoltaics Res. Appl., vol. 20, no. 6, pp. 717–726, Sep. 2012.

[7] T. Carlsson and A. Brinkman, “Identification of degradation mechanisms in field-tested CdTe modules,” Prog. Photovoltaics Res. Appl., vol. 14, no. 3, pp. 213–224, May 20 200

[8] A. Mansouri, M. Zettle, O. Mayer, M. Lynass, M.Bucher, “Defect detection in photovoltaic modules using electroluminescence imaging” 27th PVSEC proceedings