INDOOR AND OUTDOOR CHARACTERIZAITION OF a-Si:H P-I-N MODULES

F. P. Baumgartner[1], J. Sutterlüti[1], W. Zaaiman[2], T. Sample[2], J. Meier[3],

[1] University of Applied Sciences Buchs, NTB; Werdenbergstrasse 4; CH-9471 Buchs; Switzerland, www.ntb.ch/pv
Phone: 0041-81755-3377; Fax: 0041-81756-5434 ; e-mail: franz.baumgartner@ntb.ch

[2] European Commission, DG Joint Research Centre, Institute for Environment and Sustainability, Renewable Energies, ESTI, Ispra (VA), Italy, e-mail: willem.zaaiman@jrc.it;
[3] Oerlikon Solar-Lab S.A., Neuchâtel, Puits-Godet 12a, CH-2000 Neuchâtel
e-mail: johannes.meier@oerlikon.com

ABSTRACT: Indoor and outdoor electrical measurements were performed on light-soaked single-junction a-Si:H p-i-n mini-modules with respect to a cr-Si reference cell matched to the a-Si spectral characteristics by an integrated optical filter. The Simplified Global Sunlight Method SGSM was applied to analyse the outdoor performance of these a-Si:H modules. In order to check if the present outdoor spectra condition is close to the AM1.5G condition in the sensitive range between 350nm to 750nm this filtered cr-Si reference cell was used. The indoor outdoor comparison of the characterisation of this filtered reference cell shows that the solar simulator result of (14.81±0.37) mV agrees well with the result of the SGSM of (15.00±0.23) mV within their combined uncertainties (k=2). The typical temperature coefficient of the STC power obtained by indoor measurements of a-Si:H mini-modules results in (-0.201±0.03)$\%_{STC}$/°C and also agrees well with the outdoor measurement results of (-0.175±0.03)$\%_{STC}$/°C, both within their respected k=2 uncertainties. Large-area a-Si:H modules (1.4m^2) in the initial state have been monitored under outdoor conditions during winter time. The exponential decay of the fill factor is described by a time constant of 27 hours at 1000 W/m^2 irradiance.

Keywords: a-Si, Characterization, Performance, Temperature coefficient

1 INTRODUCTION

Today the first a-Si plants in the MW range are in operation and new one's are in the planning or construction stage [1]. From the investor's point of view, the most sensitive parameters to the economic success of these thin film technologies plants are the actual STC nominal values of the modules as well as its temperature coefficients, [2]. Usually standard indoor flasher equipment is applied to the characterisation of a-Si:H modules. It is well known that the a-Si:H sensitive spectral range is between 350nm and 750nm. Therefore, the indoor light source as well as the used solar reference cell [3] has to be matched to that particular range of amorphous silicon. Not only a mismatch factor close to 1 but also a constant mismatch factor during the light pulse has to be demonstrated first in order to guarantee a low measurement uncertainty [4].

In future outdoor performance characterisation also on PV plant level will have high practical relevance to a-Si modules, due to the fact that the initial degradation during the first weeks may influence the final nominal power individually. Currently little data can be found in the literature about the results in applying the above well known methodology to today's a-Si thin film modules with respect to the final measurement uncertainty of indoor and outdoor measurements.

2 INDOOR CHARACTERIZATION

The cr-Si reference cell AQ82 was used to compare the indoor and outdoor measurement of the a-Si:H solar cells. The AQ82 is equipped with an integrated optical filter to match the spectral characteristics of typical a-Si:H solar cells (AQ83, AQ84) as shown by the measured spectral response curve in figure 1. A second standard cr-Si reference cell AQ81 without filter is also analyzed. Both cells are standard reference cells from Fraunhofer ISE while the AQ82 is produced with an internal shunt to be used in outdoor applications.

2.1 Performance of the Filtered Reference Cell

The measurement results performed at ESTI on the internal shunted AQ82 reference cell are found to be (14.81±0.37) mV measured on the pulsed solar simulator SpectroLab LAPSS and (15.07±0.38) mV measured on the steady state WACOM simulator. As reference cell the standard PX201C was always used. The above results are well within the uncertainty limits of the nominal calibration value of (15.0±0.30) mV given by ISE. All uncertainty values correspond to k=2.

2.2 Spectral Photocurrent and IV Measurement

The spectral response (SR) characteristics of both crystalline reference cells AQ82 and AQ81 were measured using the standard Oriel SR measurement system [5] at ESTI (bias light 100 W/m^2).

The AQ81 is also used as the reference spectral response cell for the NTB large area SR measurement system [6]. In figure 1 the SR results of AQ82 and AQ81 are shown together with the SR characteristics of a-Si mini-modules (AQ83 and AQ84) measured using the large area Pasan SR measurement system. The AQ82 reference cell exhibits a spectral sensitivity extended by about 50nm beyond the long wavelength limit of the standard a-Si cell.

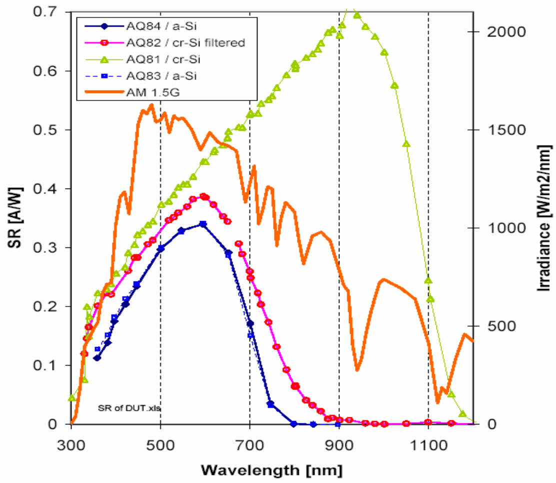

Figure 1: The relative spectral response of the two cr-Si type reference cells AQ81, AQ82 together with two a-Si mini-modules AQ83, AQ84 are shown. The standard STC AM1.5G spectrum is also plotted.

The amorphous silicon mini-modules analysed in this study were produced by the Oerlikon company. The devices AQ83, AQ84 and AQ88 consist of 26 monolithic series connected single-junction p-i-n a-Si:H cell segments with an area of each cell of about 2000 mm^2. Prior to present investigations all mini-modules have been light-soaked under one sun at 50 C and for 1000 h in order to avoid effects due to Staebler-Wronski instability.

The current voltage IV measurement results obtained from the SpectroLab solar simulator are given in table I. During the current voltage scan, of up to 1.5 ms, the irradiance value remains nearly constant [4]. A control measurement was carried out by simultaneously measuring the signal of the AQ82 and the standard reference cell PX201C (similar SR curve as AQ81 (see Fig. 1)). The change of the ratio of both reference signals during the 1.5ms scan period was smaller 0.5% indicating negligible spectral change of the light source during the pulse with respect to a-Si and cr-Si cells. A similar control measurement was also performed on the Pasan solar simulator [4]. A nearly linear decrease of the ratio of about 3% was observed during the same scanning period in the region of the falling slope of the pulse. This result indicates that for the Pasan solar simulator the use of a standard (non filtered) cr-Si reference cell like the PX201C is not recommended because the mismatch factor relative to a-Si devices is changing during the pulse.

Table I: Results of the IV characteristics of a-Si mini-modules measured using the SpectroLab LAPSS flash simulator. The PX201C cell was used as the reference cell. Uncertainty level k=2 relative to STC value.

	AQ83	AQ84	AQ88	HS81	uncertainty
I_{SC} [A]	0.2634	0.2639	0.2650	0.220	2.5%
V_{OC} [V]	22.78	22.45	22.44	19.23	0.32%
V_{MP} [V]	16.93	16.72	16.53	14.90	0.32%
FF [%]	59.39	56.89	57.07	60.30	0.72%

2.3 Change of IV Parameters with Irradiance

The change of current-voltage parameters in relation to changing irradiance were measured on the SpectroLab simulator and are shown in figure 2. The resulting values of the linear approximation for various parameters with respect to irradiance Pin is listed in table II.

Table II: Results of the change of IV parameters as a linear function of irradiance obtained by the SpectroLab simulator at 25°C. (typical standard deviation value ±0.005 see Fig. 2)

$\Delta FF/FF_{STC}$	= - 0.065 * ΔPin / 1000 Wm^{-2}
$\Delta V_{OC}/V_{OC,STC}$	= + 0.052 * ΔPin / 1000 Wm^{-2}
$\Delta V_{mp}/V_{mp,STC}$	= - 0.004 * ΔPin / 1000 Wm^{-2}
$\Delta I_{mp}/I_{mp,STC}$	= + 0.982 * ΔPin / 1000 Wm^{-2}
$\Delta I_{SC}/I_{SC,STC}$	= + 0.989 * ΔPin / 1000 Wm^{-2}
$\Delta\eta/\eta_{STC}$	= - 0.024 * ΔPin / 1000 Wm^{-2}

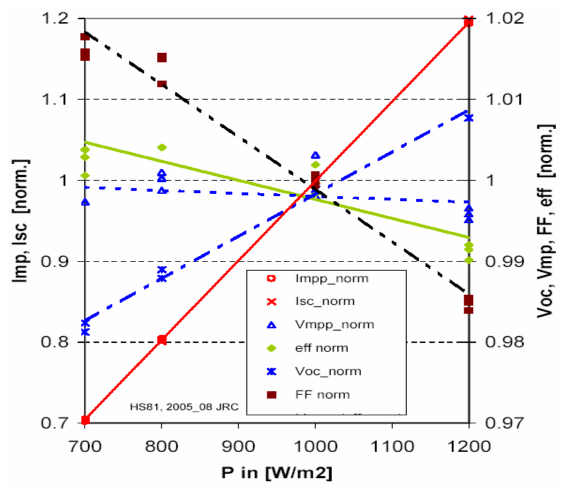

Figure 2: Measurement of the linearity of the current voltage parameters of a-Si mini-module HS81 at different irradiance values Pin performed on the pulsed solar simulator SpectroLab (reference cell PX204A see [2]) Results of linear approximation see table II.

2.4 Change of IV Parameters by Temperature -Indoor

Understanding the change of the performance of a-Si modules it is essential to describe the real outdoor temperature behaviour of this technology to aid the prediction of their energy rating. Results of the indoor temperature coefficient measurements are found in table III, the outdoor measurements are discussed in section 3.2.

Table III: Results of the indoor measured TC using the Pasan simulator in the temperature range between 25°C and 60°C corrected to an irradiance value of 800 W/m^2. The values are given in % change relative to the STC values of the individual values $TC_X/X(25\ °C)$; k=2.

[% $_{STC}$/°C]	AQ84	AQ88	HS81	uncertainty
I_{SC}	+0.082	+0.075	+0.067	±3.2 mA/°C
V_{OC}	-0.338	-0.321	-0.323	±0.46 V/°C
η	-0.181	-0.201	-0.260	±0.17 %/°C
V_{MP}	-0.327	-0.298	-0.377	±0.36 V/°C
FF	+0.084	+0.100	-	-

3 OUTDOOR CHARACTERIZATION

The results of the outdoor measurements performed on the two-axis solar tracker system at ESTI/Ispra on selected clear sky days in June and July 2006 are discussed here. On the 2006-06-30 the outdoor spectrum (Fig. 3) was measured each 6 minutes by the use of the spectroradiometer OL750 (350nm to 2500nm in 2nm steps). The total irradiance was also achieved by the sum of the pyrheliometer readings as practical absolute cavity radiometer and the diffused irradiance value measured by a shaded pyranometer (similar experimental setup see [8]). The reference cells were mounted on a cooled plate to a junction temperature of 25°C±2°C.

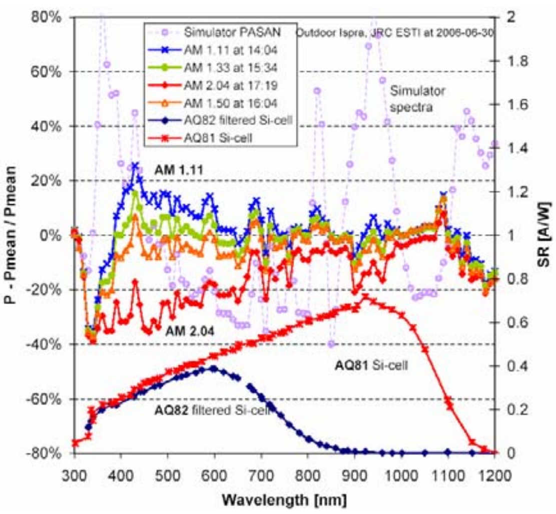

Figure 3: Outdoor spectra measured on the 2006-06-30 pm at ESTI. The scaling is given as the difference to STC AM1.5G spectrum relative to Pmean=0.913 W m^{-2} nm^{-1}.

In a first step the behaviour of the AQ82 reference cell is analysed relative to the total irradiance values determined with the lowest available combined measurement uncertainty [8]. According to the simplified global sunlight method SGSM, the intercept of the linear approximation of the analysed signal as a function of air mass AM values gives the STC value at AM=1.5 [9, 10]. In figure 4 it can be shown that for the period from 2006-06-29 to 2006-07-03 most of these intercepts at AM 1.5 are within 1% of the given calibration value of AQ82 (section 2.1). But on the other hand two plots are up to 3% away from that value. For example in the afternoon of 2006-06-30 pm a clear sky day the value is 1.5% above the AM1.5 value compared to the measurement in the morning 2006-06-30 am. No significant differences observed by analysing the ratio between direct and diffused irradiance for that day (Fig. 5). This result is in accordance with other studies of the SGSM [10].

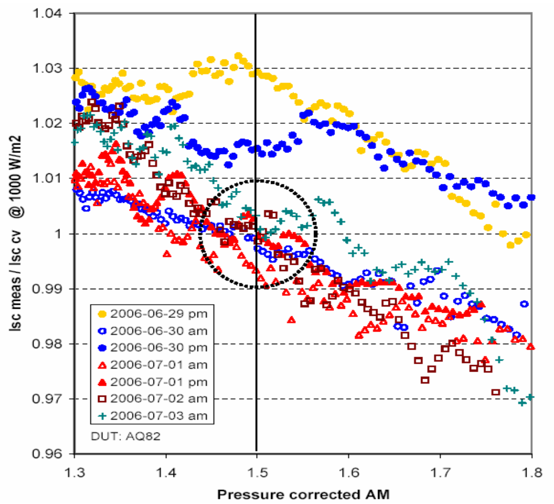

Figure 4: Simplified global sunlight method to determine the STC value of AQ82 at AM1.5. The scaling of the measured signal of AQ82 is relative to the nominal calibration value of 15.00mV and the relative to the total irradiance to 1000 W/m^2 (pressure corrected AM used).

Therefore, a modification of the SGSM is proposed in which the signal of the filtered reference cell (like AQ82) is used to check if that result of the SGSM applied to the reference cell gives AM1.5 reference values within 1% of the expected calibration value of the reference cell.

Only under that selected spectral outdoor conditions the SGSM may be applied to a-Si devices under test. Figure 6 shows that the SGSM applied to the measured I_{sc} current of the a-Si mini-module AQ84 is proportional to the simultaneously measured signal of the shunted reference AQ82. By executing the modified SGSM as described above the p.m. values at 2006-06-30 in figure 6 are eliminated. Due to the fact that the module temperature around AM1.5 was about 55°C in the morning and around 65°C in the afternoon the measured I_{sc} values at the appropriated spectra are higher than the measured indoors values.

The measured I_{sc} values relative to the filtered reference (all values are scaled to their nominal indoor measurement results) are given in figure 7. The ratios in the AM range between AM1.3 to AM1.8 are nearly constant which indicates that the spectral sensitivity of the reference cell (AQ82) is matched to the a-Si DUT (AQ83 and AQ84). Taking the TC values of AQ84 from table III, the outdoor morning (am) value of I_{sc} of 1.040 can be corrected to the final factor of 1.015 at 25°C. The afternoon (pm) value of 1.050 can be corrected to the final value of 1.018 at 25°C. Thus both final temperature corrected outdoor results are well within the IV indoor measurement uncertainty limits of 2.5%.

In figure 3 it is shown that during the afternoon the power in the a-Si sensitive range from 400 to 700nm is reduced relative to the 700 to 1100nm region while the air mass value is increased from AM 1.1 to AM 2.04. Therefore, the ratio of the AQ81 signal of the non-filtered cr-Si divided by the AQ82 signal is increasing with AM-value as it can be seen in figure 7 and table I.

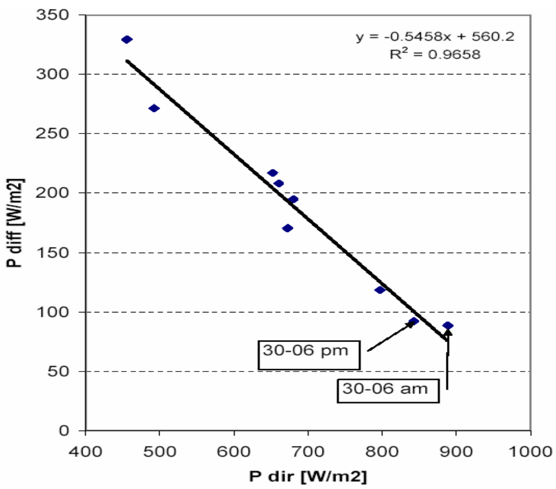

Figure 5: Direct and diffuse irradiance at AM 1.5 on the above days 2006-06-29 to 2006-07-03 each am and pm values shown by one data point.

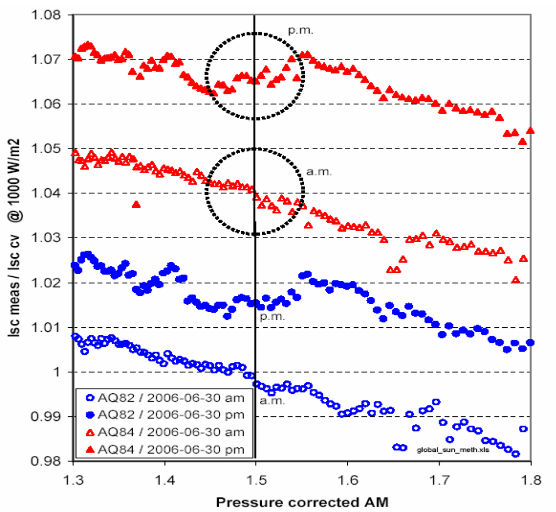

Figure 6: Simplified global sunlight method applied to AQ84 a-Si mini-module using the measured irradiance values from the pyrheliometer and the shaded pyranometer (AQ84 was not cooled to 25°C).

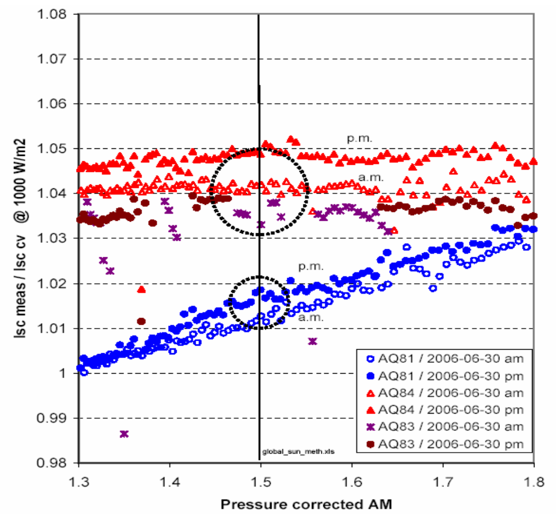

Figure 7: Global sunlight method applied to AQ84 and AQ83 a-Si mini-modules (not cooled) using measured irradiance values of the filtered reference cell AQ82. For comparison the measured AQ81 (non-filtered cr-Si) values are normalized also to the AQ82 values.

3.1 Absolute Spectral Response Method

The STC short current $I_{DUT,STC}$ of the ESTI reference cell PX201C as part of the World Photovoltaic Scale is well known. According to the following formula the absolute SR characteristics of the PX201C is given by the defined AM1.5G spectrum.

$$I_{DUT,STC} = \int_{\lambda_1}^{\lambda_2} P_{AM1.5G}(\lambda) \cdot SR_{DUT}(\lambda)\, d\lambda = I_{DUT,CV}$$

$$I_{DUT,IN} = \int_{\lambda_1}^{\lambda_2} P_{IN}(\lambda) \cdot SR_{DUT}(\lambda)\, d\lambda$$

Figure 8 shows the measured I_{sc} value of the PX201C reference cell relative to the calculated I_{sc} value of PX201C by using the measured outdoor spectrum (Fig. 3) P_{IN} and the known SR characteristics.

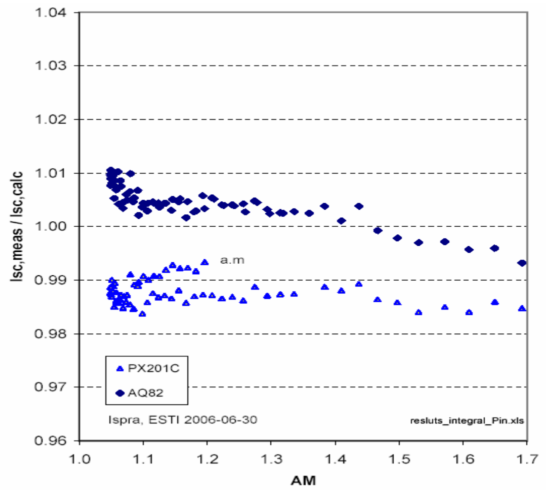

Figure 8: Measured short-circuit current values of references AQ82 and cr-Si PX201C [9] in outdoor conditions shown relative to the calculated $I_{sc,\ calc}$-values based on the measured outdoor spectra P_{IN} versus AM.

By that reference measurement it may be suggested that the measured outdoor spectra P_{IN} is scaled absolutely by an uncertainty below 2% (Fig. 8).

3.2 Change of IV Parameters by Temperature - Outdoor

The measured IV characteristic of the a-Si mini-module AQ88 mounted on the two-axis solar tracker was analyzed to determine its temperature coefficients. During the period around noon between 11:16 to 13:16 the global irradiance was nearly constant at (1026 ± 5 W/m^2) at AM 1.06 while the change of module temperature was about 10°C (Fig. 9).

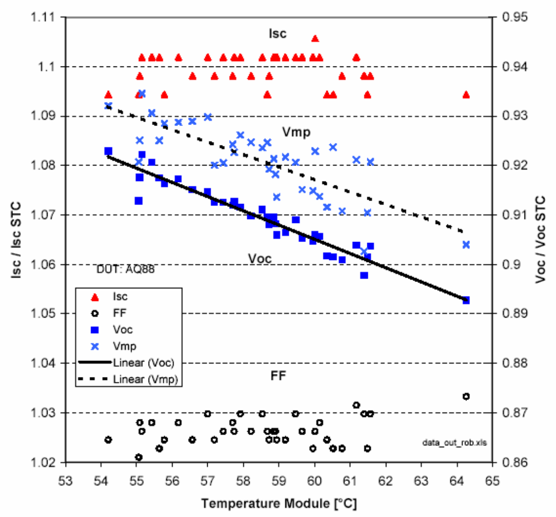

Figure 9: Outdoor TC characterization of a-Si mini-module AQ88 mounted on the 2-axis solar tracker at ESTI/Ispra on 2006-06-30; fitted TC values relative to the STC values are -0.29%/°C of V_{oc}, and -0.25%/°C of V_{mp} both with standard deviation values of ±0.04%/°C.

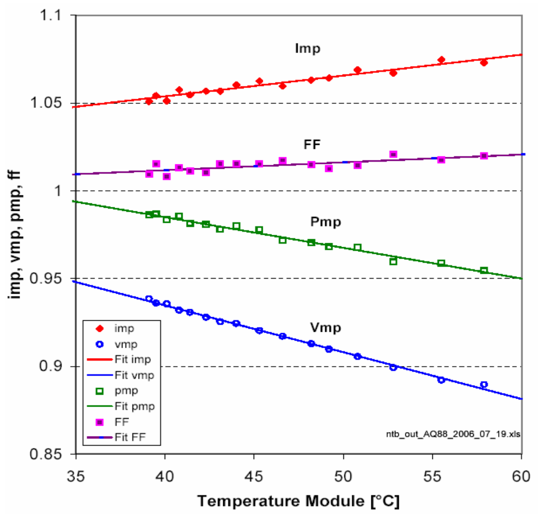

Figure 10: NTB outdoor TC characterization by active cooling of the a-Si mini-module AQ88 from 58°C to 37°C during the period 11:25 to 11:40 on the 2006-07-19; Pin =908 to 941 W/m^2 measured by ISE Ref AQ82; AM 1.23 to 1.20 ; The straight fit lines are corresponding with the following TC values: TC_{Vmp}=-0.267%$_{STC}$/°C; TC_{Imp}=+0.119%$_{STC}$/°C; TC_{FF}= +0.045%$_{STC}$/°C; TC_{Pmp}=-0.175%$_{STC}$/°C uncertainty ±0.03%$_{STC}$/°C.

Additionally the TC of the same device was measured under outdoor conditions at NTB by active cooling the a-Si mini-module by the use of Peltier elements. Due to the higher range in module temperature also the TC of FF and I_{sc} could be determined. The obtained TC values resulted by the applied three independent measurement methods (indoor table III, outdoor at ESTI figure 9 and outdoor at NTB figure 10) agree well within the given uncertainty values.

3.3 Outdoor Degradation of the Fill Factor

The light-induced degradation behaviour under outdoor conditions of a 1.4 m^2 single-junction a-Si:H p-i-n module in the initial state (produced by Oerlikon) was studied by the decay of the FF. The outdoor measurements were started with the a-Si module in the non-degraded, initial state, as produced on the 2005-12-13. The data acquisition system recorded an IV curve every minute together with the module temperature and the in plane irradiance using a CM11 pyranometer.

In figure 11 a data filter was applied to the whole set of the measured IV curves. Only that FF values are shown where the global irradiance values were within the interval 700 to 750 W/m^2 for at least a period of 30 minutes with a typical standard deviation of the irradiance of 26 W/m^2. This condition usually holds for clear day sky conditions. The degradation of FF is fitted by a standard exponential decay characteristic. The fitted time constant was found to be 27 hours at average 1000 W/m^2 where 63% of the final decay of FF already occurred. During the initial exposure period in winter time the module temperature was between 20 °C and 30 °C for a typical clear sky day.

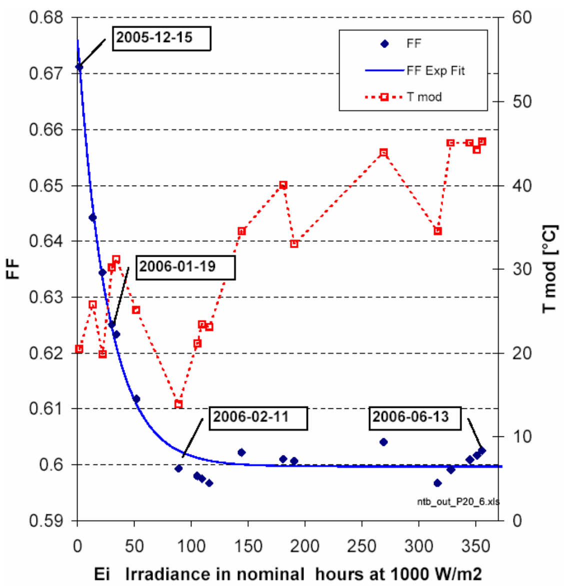

Figure 11: Degradation of the fill factor measured during outdoor exposure of the a-Si Module P20-6 over a period of six months versus the overall energy seen by the module since starting the outdoor exposure. The module temperature is also shown for that selected irradiance conditions on typical clear sky days (fixed mounted at 30° inclination to south direction at NTB in Buchs, Switzerland).

A change in module temperature of about 20 °C (during summertime) will result in an increase of the FF by only 1% (see TC values of FF in figure 10). Finally it was found that the change of the FF is the most suitable indicator to determine the status of degradation/stability of a-Si modules if outdoor measurements within a small interval of irradiance values of about 50 W/m^2 are analysed.

Future work will concentrate on the study of the time constant starting the first outdoor exposure at higher module temperature values together with the final degradation value for a-Si modules produced under slightly different production conditions.

4 DISCUSSIONS and CONCLUSION

In reference [8] the authors found an expanded measurement uncertainty of 1% by the use of the SGSM without a spectroradiometer by restricting to a measurement period of three days in autumn or spring. The modified SGSM proposed here uses the signal of a spectral matched reference cell to extract these outdoor conditions from the analysed data set which deviate from the STC reference cell values not more than 1%.

In comparison to the uncertainty analyses of the SGSM in [8, 9, 10] it is estimated that uncertainty values in I_{sc} of 1.6% (k=2) should also be valid for the present measurement of the cooled filtered cr-Si reference cell (AQ82). This uncertainty budget of 1.57% (k=2) consists of 0.64% (k=2) as type B uncertainty [9] and 1.43% (k=2) type A uncertainty resulting from the standard deviation of the linear fit results versus AM (in figure 4 all four morning “am” curves used). By applying the slightly modified SGSM to the outdoor measurement taken during summer time the results agreed to the indoor IV measurements under flash simulators within the given uncertainty values (I_{sc} indoor ±2.5%; SGSM ±1.6%). Finally it has to be noted that the uncertainty of the temperature coefficient of the I_{sc} has to be included in the overall SGSM uncertainty analyses, if the modules are not cooled to constant 25°C. The main advantage of the SGSM method is that it can be adapted to analyse the performance of PV plants, at reasonable costs for the measurement setup in future.

Three different indoor and outdoor TC measurement methods of the IV characteristics are found to be well within the given uncertainty limits. The degradation of the fill factor was studied by selecting outdoor data sets in a narrow irradiance interval of about 50 W/m^2.

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5 REFERENCES

[1] A. Jäger-Waldau; J. of Non-Crystalline Solids 352(2006) p1922-1927; and Photon, June 2006
[2] R. Kenny, E. Dunlop, T. Sample, K. Reiz, D. Anderson; Euro PV Conf. Rome, 2002
[3] E. Dunlop, W. Zaaiman, H. Ossenbrink, C. Helmke; Euro PV Conf. Barcelona 1997;
[4] R. Galleano, E. Dunlop, D. Halton; Euro PV Conf. Paris 2004
[5] E. Dunlop et. al.; Euro PV Conf. Glasgow 2001
[6] S. Janki, J. Sutterlüti, J. Meier, F. Baumgartner; present Euro PV Conf. session 3DV-3.49
[7] U. Kroll, J. Meier et al. present Euro PV Conf, session 3DP.1.5.
[8] H. Müllejans et. al. Meas. Sci. Technol. 16(2005) 1250 - 1254
[9] H. Müllejans, W. Zaaiman, E. D. Dunlop, H. Ossenbrink; Metrologia 42 (2005) 360-367
[10] W. Zaaiman et. al. ; present Euro PV Conf., 1BO82; see SGSM topics in chapter 2.1