WEAK LIGHT PERFORMANCE AND SPECTRAL RESPONSE OF DIFFERENT SOLAR CELL TYPES

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ABSTRACT: A large number of possible PV-powered products should be able to operate under *indoor* lighting conditions. In order to make good product designs of indoor operated PV-devices (*ipv*), a more extended dataset of PV characteristics than just standard test condition (STC) parameters is required. Within the SYN-Energy project framework, which aims to improve design methods for PV-powered consumer devices, this paper presents results of IV-curves measured for solar cells of different technologies at irradiance levels between 1…1000W/m^2. The resulting European cell efficiencies are calculated. In addition, measurements of the spectral responses at different bias light intensities and spectra were performed. By adopting the measurement findings to indoor irradiation scenarios, we outline the impact on *ipv* energy yields regarding spectral response and the efficiency decrease towards low light levels. This is performed by applying a simplified daylight factor approach to the measured characteristics of *commercial* available PV at lower/indoor light levels and implementing solar cells spectral response using de-rating factors.
Keywords: solar cell efficiencies, spectral response, solar powered consumer products, indoor photovoltaic, STC

1 INTRODUCTION

Solar cell efficiency is an important input parameter in PV-powered product design. Often, only limited space is available for the solar cells to be integrated. Cell efficiency can even become a criterion of principal system feasibility. As a basic parameter, cell efficiency serves as an input in calculating the optimal system configuration, e.g., as a cost related trade-off between the storage unit and its lifetime, PV size and its efficiency, and finally the demand side (with correlated consumption profiles). Although these calculations are well known for autonomous PV systems, e.g. [1], device integrated PV-systems, *especially* when used *indoors*, become more complex to model. Different irradiation conditions compared to those *outdoors* require a more detailed knowledge of solar cell characteristics than is described with the current standard test condition (STC), wherein the efficiency definition is limited to an irradiation level of 1000 W/m^2 at AM1.5 spectrum.

Whether the user of a solar powered device will be satisfied is supposed to be strongly related with the overall energy balance of demand and (solar) energy supply, which is the overall solar fraction of energy flow. Not surprisingly, one observes that the uncertainty in energy consumption data combined with the possible variations in intensity of use and irradiation results in large variations in the expected solar fraction [2]. Therefore, this paper intends to determine indoor PV (*ipv)* energy yields linked to irradiation level classes, enabling product designers to reduce uncertainty of estimated light harvesting potentials of *ipv*, and resulting solar fractions in dedicated devices respectively.

Calculating the energy yield of PV indoors require both indoor irradiation levels as well as spectral distributions. To get access to PV characteristics at indoor light levels as well as the specific spectral response (SR) characteristics, a cell survey has been carried out. In this paper the measurement results of commercial available solar cells from different manufacturers and different cell technologies are presented. Cell samples have been investigated regarding their IV-characteristics down to light intensities in a range three orders of magnitude below STC. Also the SR of the test samples was investigated, using two different bias light intensities and spectra. The method of estimating *ipv* energy harvesting potentials is to link measured PV performances to different daylight factors of indoor irradiation conditions. To accommodate this, we introduce de-rating factors on the spectral mismatch (by using selective absorption characteristic of a standard window system), and calculate the impact of weak light cell performance using distributions of irradiation classes.

2 EXPERIMENTAL

Spectral response measurements have been taken at the Energy Research Centre of the Netherlands (ECN), IV-measurements were performed using a SPECTROLAB solar simulator at ECN and a WACOM solar simulator at Utrecht University.

IV-characteristics were measured in a light intensity range between 1-1000 W/m^2, using different grey filters in the light path of the sun simulator. Dark current curves of selected cell samples have been measured as the parallel (shunt) resistance R_p can be determined by the linear slope of the reverse dark current. The serial resistance R_s can be calculated from two IV curves at light intensities of 500 W/m^2 and 1000 W/m^2, respectively, according to IEC 891 [3]. In addition, the basic cell parameter set (diode saturation current and quality factor, short circuit and maximum power point voltages and currents) was calculated automatically at each measured IV-curve and has been fed into a database for future research.

This paper limits its focus on the resulting cell efficiencies along with the arising energy yields in *ipv* products. Cell efficiency was calculated by

$$\eta(G)=\frac{FF\cdot I_{sc}\cdot V_{oc}}{G} \quad (1)$$

where light intensity itself was calculated from the measured I_{sc} of a calibrated mc-Si reference cell, hence I_{sc} is well known to be directly proportional to light intensity (G) in the used light intensity range:

$$G = \frac{I_{sc,ref}(G)}{I_{sc,ref}(G_{1000} \cong 1000\,W/m^2)} \qquad (2)$$

The indoor environment typically has smaller temperature ranges than might occur outdoors, therefore temperature dependence within *ipv* devices is supposed to have no important influence regarding efficiency. Nevertheless, the measurement temperature was fixed at 25 °C to be compliant to STC. The correction factor of spectral mismatch induced through the wavelength dependent absorption of the filters is far below error tolerances and has therefore been neglected.

3 RESULTS AND DISCUSSION

3.1 IV-curve measurement results

The efficiency decreases exponentially at weaker light intensities, as V_{oc} decreases with the well-known logarithmic slope. Therefore it is illustrative to plot efficiencies as a function of irradiation intensity on a logarithmic scale. In Figure 1 the resulting cell efficiencies of selected c-Si cells received from two different cell manufacturers are shown.

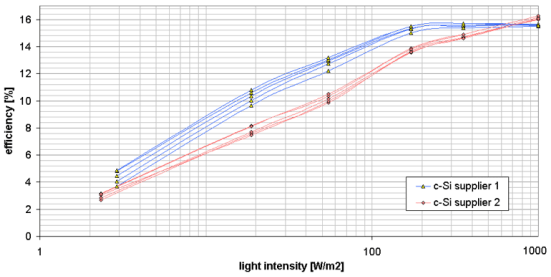

Figure 1: *Measured absolute efficiencies as a function of irradiance at c-Si cells from two cell manufacturers*

As can be seen in Figure 1, cell efficiency in the highest intensity decade (100-1000 W/m^2) does not vary much. A two percent decrease at supplier one and a slight increase towards weak light at the samples from supplier one can be seen. In this intensity decade, the serial resistance determines the efficiency at STC irradiation level. Towards lower irradiation less losses are associated to the serial resistance, explaining the slight increase in cell efficiency at samples from supplier one. Below 100 W/m^2 light intensity, almost all samples show a linear decrease on a natural logarithmic scale. In this low light level range (most often encountered *indoors*), it is the parallel resistance and the second diode characteristic affecting cell efficiency. Because these parameters do vary remarkably dependent on the individual cell, a wider spread in cell efficiency towards weaker light compared to STC light level can be seen. This is especially true for the measured multi crystalline silicon cell samples, as can be seen in Figure 2. Beside different overall performance differences, which can be related to different manufacturers providing test samples but also to sun simulator uncertainties, a factor two difference is found for cells from *single* suppliers (see insert in Fig. 2). These cells show almost the same performance under STC conditions and are likely to belong to the same power class.

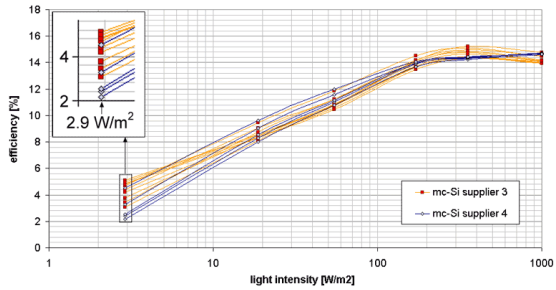

Figure 2: *Measured absolute efficiencies as a function of irradiance of c-Si cells from cell manufacturers*

The decrease of solar cell efficiency towards weak light is very dependent on the cell technology, as has been published earlier in another PV weak light performance cell survey [4], and in theoretical modelling of c-Si, a-Si:H and CIGS cells [5]. To give an impression on the found ranges of efficiency decrease dependent on selected cell technologies, Figure 3 shows ranges of efficiencies relatively to STC measured within the present cell survey as well as derived from literature.

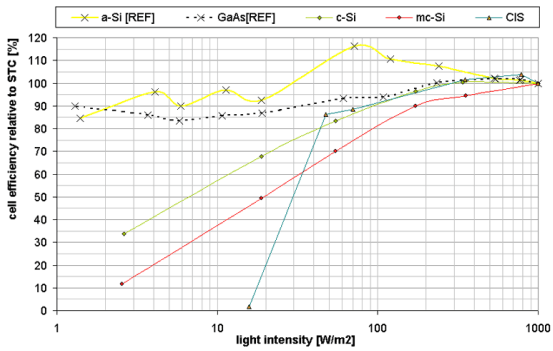

Figure 3: *Comparison efficiencies relatively to STC; mc-, c-Si and CIS solar cell performances measured in cell survey, a-Si PIN-PIN and GaAs cells from [6]*

The highest decrease in efficiency can be seen for CIS cells, although it has to be mentioned that research rather than commercial available samples have been measured. The decrease in efficiency results from a decrease of MPP and open circuit voltage. Crystalline silicon based cells show a broad range in efficiency decrease, dependent on whether mono or multi crystalline silicon cells are concerned. Because of its naturally very high parallel resistance, a-Si:H samples show the lowest decrease on an overall relatively low efficiency level at AM1.5 spectra.

3.2 European efficiencies

By describing irradiation level classes (ΔG) with weighting factors ($f_{\Delta G}$), the overall energy yield can be determined more precisely than just using the current STC standard. Each irradiation class can be associated with specific (averaged) cell efficiency dependent on the irradiation level. Table I outlines the impact of efficiency decrease on possible energy yields under AM1.5 spectra under European outdoor irradiation conditions. The found deviations in efficiency of the worst and best performing cell samples of crystalline silicon cells (Fig. 1, Fig. 2) as well as averaged efficiencies measured at CIS and a-Si:H samples (Fig. 3) are linearly combined to a weighted

average. For this method a certain irradiance distribution has to be assumed. Here, frequencies of occurring irradiance level classes are adopted from the widely used European efficiency in the inverter technology, as was introduced by Grunow *et.al.* on energy yields related to different shunt resistance in industrial solar cells [7].

$f_{\Delta G}$	0.03	0.06	0.13	0.10	0.48	0.20	η_{EU}	η_{STC}
ΔG *[W/m²]*	0-50	50-100	100-200	200-300	300-500	500-1000	**0-1000**	**1000**
a-Si[6]	*95*	*112*	*101.5*	*104*	*107.5*	*110*	**107**	**100**
CIS	*37.5*	*88.5*	*92.3*	*97.4*	*101.4*	*102.5*	**97.3**	**100**
c-Si 1	*13.2*	*14.2*	*15.2*	*15.5*	*15.6*	*15.5*	**15.4**	**15.5**
c-S. 2	*9.8*	*10.8*	*13.4*	*14.4*	*14.5*	*15.5*	**14.2**	**16.0**
mc-Si3	*10.0*	*12.5*	*14.2*	*14.8*	*14.9*	*14.8*	**14.5**	**14.5**
mc-Si4	*7.8*	*11.8*	*12.6*	*13.3*	*13.6*	*14.1*	**13.3**	**14.4**

Table I: *Measured efficiencies in percent (a-Si [6] and CIS relative to STC) used to calculate Europ. Eff. (η_{EU})*

However, as this calculation is limited to single cell characteristics, calculations cannot be extrapolated to solar modules or even noteworthy large-scale PV systems. Module efficiency is determined by mixing cells of various characteristics, system configurations and its interaction (e.g. inverters, charge controllers, etc.) can raise even higher relevant parameters. But Table I certainly accentuates the need of an extended STC parameter set, at least for the *ipv* field, where weighting factors are more likely to describe light levels in the 1-100 W/m2 decades rather than having almost half the influence at a half sun averaged irradiation.

We therefore propose the development of an indoor efficiency standard, based on a number of irradiation level classes prevailing in indoor environments. Further work on identifying these classes will be pursued by us, however, section 4 already uses this approach in a simplified way.

3.3 Spectral response measurement results

The spectral response usually is measured at a bias light (0.5 sun) illuminating the cell, measuring the short circuit current when additionally illuminating the cell sample with chopped monochromatic light. The complete measurement procedure of SR measurements is described elsewhere [8].

In order to emulate realistic indoor irradiation conditions, the bias light intensity as well as the intensity of the monochromatic light was lowered to approximately 0.1 suns. Spectral response measurements were also performed using the artificial lighting of the lab as a bias light source, as spectral response under indoor environment conditions is of interest. Figures 4 to 6 show a selection of results for cells of different technologies.

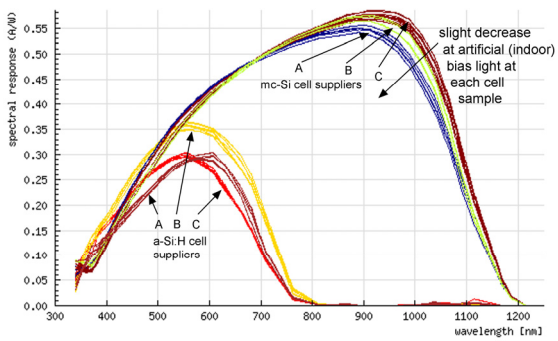

Figure 4: *Spectral response of a-Si:H, mc-Si samples*

Different peaks in SR of a-Si:H cells can be explained by different doping concentrations used in processing cells; the found decrease in SR at mc-Si samples is marginal and too small to influence efficiency (Fig.4). The difference of SR in the infrared at supplier A, B, and C, in c-Si samples can be explained in differences of the back surface field (BSF), CIS samples show the typical wide range in SR (Fig.5).

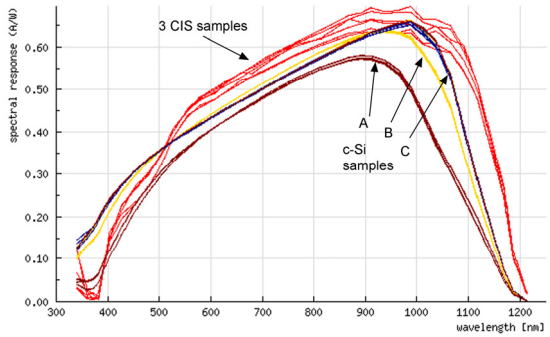

Figure 5: *Spectral responses of c-Si and CIS samples*

The found increase in SR at the high efficiency cell (Fig.6) can be explained by the role of defects and impurities [9]. As these centres become more occupied at higher bias light intensities, electron hole pairs induced by monochromatic light will have a higher contribution to the measured current.

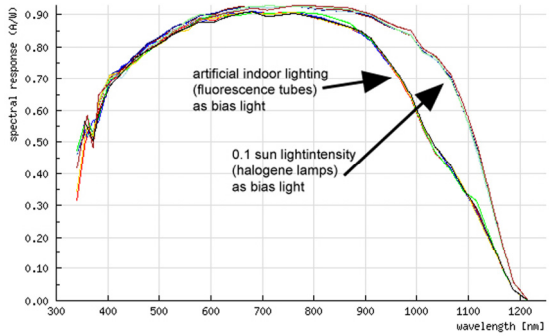

Figure 6: *Spectral responses of three equal c-Si samples*

4 INDOOR PV CHARGE GENERATION

4.1 Indoor Irradiation Conditions

Regarding indoor irradiation conditions two major differences compared to available (sun-) light outdoors can be distinguished.

Firstly, the overall light intensity is orders of magnitudes below the one outdoors. The commonly used relation between out- and indoor light levels is the daylight factor (DF), defined as the ratio of indoor divided by outdoor light intensity. This factor depends on many variables; for the benefit of this work (calculating possible energy yields of *ipv*) we will use distinct DF's of 1%, 5% and 10% respectively.

Secondly the spectrum of indoor and outdoor irradiation differs. Further descriptions of indoor light most often have photopic eye responsivity ($V_{(\lambda)}$) implemented already with all values outlined in Lux. Also spectral standards (from CIE) like the D65 diffuse sky spectrum [10] are limited to wavelengths between 360 and 760 nm. As measurement results of SR show (Fig.4-6) irradiance information in wavelength ranges far above than those defined for Lux and in D65 are required.

Last but not least artificial lighting has to be implemented indoors, which is most likely not of interest outdoors.

4.2 Indoor PV charge generation

We now calculate possible electricity conversion sums of PV indoors ($E_{PV,in}$), by multiplying the particular efficiency of PV at certain irradiation level classes ΔG, with the overall energy flow E(ΔG) related to the certain class, as was performed in section 3.2:

$$E_{PV,in} = \left(\sum_{\Delta G,min}^{\Delta G,max} \eta_{PV}(\Delta G) \cdot E(\Delta G) \cdot f_{mm,MPP}(\Delta G) \right) \cdot f_{mm,\lambda} \quad (3)$$

where ΔG,min and ΔG,max indicate the minimum and maximum of defined irradiation classes. Additionally, the mismatch between the actual (V_{real}) and the optimal operating voltage (V_{mpp}) of solar cells is considered using a de-rating factor ($f_{mm,MPP}$). The spectral mismatch between AM1.5 and estimated indoor spectrum is described by another de-rating factor ($f_{mm,\lambda}$).

$$f_{mm,MPP} = \sum_{G,min}^{G,max} \frac{V_{real}(G)}{V_{MPP}(G)} \quad and \quad f_{mm,\lambda} = \frac{Jsc}{\int_0^\infty I_\lambda d\lambda} \quad (4)$$

In reality V_{real} mostly is a floating battery voltage. For simplification V_{real} is supposed to be a constant set to a V_{mpp} output voltage at (for optimistic energy yields) 50% irradiation level. The voltage de-rating factor was then calculated relative to V_{real} out of the specific V_{mpp} dependant on light intensity.

The spectral mismatch between AM1.5 and the available light in the indoor environment is taken into account using a spectral de-rating factor ($f_{mm,\lambda}$). In a first order approach this factor can be assumed as the ratio of the lights' spectral properties available indoors and the respective spectral response of the distinct PV technology. The available indoor spectrum is calculated out of AM1.5 and wavelength dependent transmission values of a sample window system, derived from [11]. A free ventilated double glazing window system was assumed as a common standard, having mismatch factors of 0.95 (a-Si), 0.86 (CIS) and 0.87 (c-Si, mc-Si) as a result.

4.3 Resulting cell efficiencies indoors

By applying equations (3) and (4) on the measured efficiencies in section 3, thus taking into account the V_{MPP} distributions over light intensity as well as the spectral mismatch caused by the window as a wavelength dependent filter, the efficiencies dependent on three DF have been calculated and are listed in Table II. For the benefit of possible comparisons, the European efficiency and STC efficiency is also listed in the table.

DF:	$\eta_{DF=1\%}$	$\eta_{DF=5\%}$	$\eta_{DF=10\%}$	η_{EU}	η_{STC}
a-Si[6]	*97*	*92*	*97*	107	100
CIS	*0*	*14*	*40*	97.3	100
c-Si 1	*5.0*	*8.1*	*9.8*	*15.4*	*15.5*
c-Si 2	*3.2*	*5.7*	*7.4*	*14.2*	*16.0*
mc-Si 3	*4.0*	*7.1*	*8.7*	*14.5*	*14.5*
mc-Si 4	*2.1*	*5.3*	*7.0*	*13.3*	*14.4*

Table II: *Calculated efficiencies dependent on SR and efficiency decrease towards low light levels*

Clearly efficiencies calculated for various DF values are, beside a-Si solar cells, (much) lower than the European and STC efficiencies.

5 CONCLUSIONS

Efficiencies of many commercial available solar cells have been measured at light intensities between 1 and 1000 W/m^2. The daylight factor approach shows that *indoor* energy yields are far lower than obtained with rated efficiencies. The mismatch of solar cell SR at AM1.5 with a calculated indoor spectrum and a sub optimal voltage fit of actual and theoretical possible cell voltages outline a further performance decrease. These lower values clearly affect the yearly yield and should be taken into consideration in product design, as overestimated solar fractions might negatively influences user valuation of solar-powered consumer products.

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