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Experimental study of variations of the solar spectrum of relevance to thin film solar cells

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Abstract

The influence of variations in the incident solar spectrum on solar cells is often neglected. This paper investigates the magnitude of this variation and its potential influence on the performance of thin film solar cells in a maritime climate. The investigation centres on the analysis of a large number of measurements carried out in Loughborough, UK, at 10 min intervals over a period of 30 months. The magnitude of the spectral variation is presented both on a daily and a seasonal basis. Of the different thin film materials studied, amorphous silicon is shown to be the most susceptible to changes in the spectral distribution, with the "useful fraction" of the light varying in the range +6% to −9% of the annual average, with the maximum occurring in summer time.

Keywords: Spectral radiation; Spectral variation; Spectral effects; Thin film solar cells; Seasonal variation

1. Introduction

Photovoltaic systems are often designed on the basis of standard meteorological data. Modern thin film devices, however, have a band gap significantly different from that of standard crystalline silicon devices (c-Si), and thus exhibit a different spectral response. This paper examines the importance of this factor in relation to variations in the solar spectrum for the three thin film technologies currently

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commercially available, namely amorphous silicon (a-Si), copper–indium, gallium–diselenide (CIGS) and cadmium telluride (CdTe). This paper is focused on relative spectral effects, i.e. effects that can explain changes in the efficiency of solar cells and thus their performance in practice.

Spectral information is not included in standard meteorological data which usually gives only the absolute global irradiation incident (i.e. integrated across all wavelengths) on a horizontal plane. The significance of neglecting the spectral effects with respect to the performance of thin film devices will depend on the particular technology used since each technology has a characteristic spectral response and, associated with this, an effective spectral range. These ranges are illustrated in Fig. 1 alongside the standard AM1.5G spectrum. The importance of spectral effects has been demonstrated by several authors on the basis of computer simulations [1,2] reflecting a relatively low number of measurements. There is little reliable data covering bad weather conditions as the spectroradiometers used to conduct these measurements are usually not environmentally sealed.

Solar Cells are normally tested under the agreed Standard Test Conditions, which specifies the AM1.5G spectrum. There is only limited knowledge about the influence of the seasonal variation of the incident spectrum, and even less for a maritime climate such as the UK's. Investigations have been undertaken for southern Germany and in the US by Nann [3] and Nann and Emery [4]. Parretta et al. [5] investigated this effect at Portici in Italy on the basis of measurements taken during good weather conditions. Berman et al. [6] have investigated spectral effects in the Negev desert in Israel. The need for further data sets becomes clear when comparing the dependence of the spectral factor used by Berman et al. (which is defined

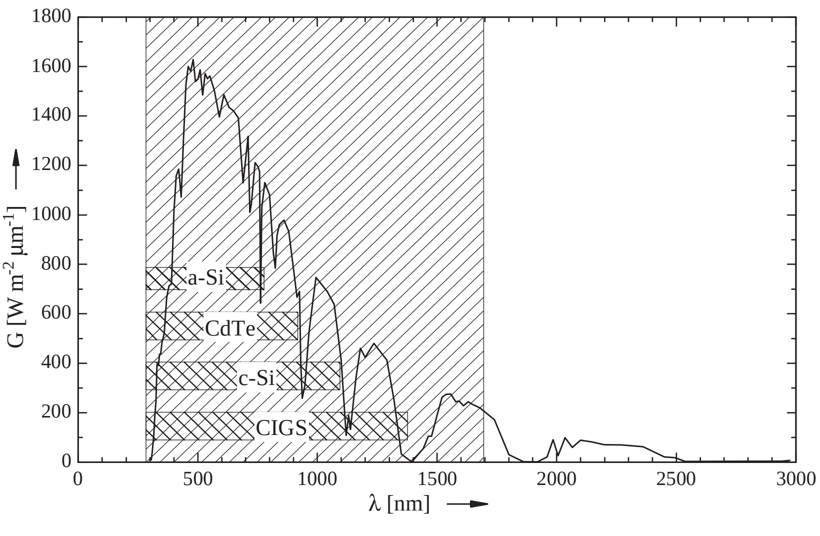

Fig. 1. AM1.5 spectrum and corresponding spectral response of different solar cell materials. The measurement range of the spectroradiometer used in this work is indicated by the larger hatched area. The spectral response of various materials is indicated by the boxes.

similarly to the useful fraction used in this work) on air mass, with the dependence found in this work. Berman et al. [6] report a linear relationship, something that is not found in the UK as will be shown in Fig. 2.

Fabero and Chenlo [7] and Merten [8] model the spectral mismatch with a spectral mismatch factor for the short circuit current of crystalline and amorphous silicon devices. A more comprehensive approach was taken by Hirata and Tani [9], who used a pyranometer and 6 filters up to a maximum wavelength of 1200 nm and investigated the effect of the spectral changes on a-Si and c-Si devices. However, all these investigations were undertaken in climates distinctly different from the UK's (and similar maritime climates) and thus specific investigations are needed to underpin thin film performance estimations appropriate to these locations. Only a limited amount of spectral data are available for the UK since, prior to the Loughborough installation, there were no spectroradiometer installations that could operate on a continuous basis. Moreover, to the authors' knowledge, no data have been presented describing the influence of daily variations in incident spectra nor on the influence of the detector used. The present study helps to address the lack of data available to the community, and uses this to examine the impact of spectral variation on device performance.

2. Experimental arrangement

To date, all published investigations known to the authors of incident radiation spectra have been conducted using silicon detectors only. This limits the spectrum to those wavelengths that crystalline silicon devices can respond to, i.e. up to 1100 nm. In contrast, the system installed at the Centre for Renewable Energy Systems Technology (CREST) at Loughborough University utilises two detectors, a Si detector which is used for the spectral range up to 1000 nm and an InGaAs detector for the region up to 1700 nm. The overall spectral response of the system is indicated by the hatched region in Fig. 1.

The incident spectral solar irradiation at Loughborough has been measured using this spectroradiometer. The spectroradiometer was commissioned in April 1998 and has been in continuous operation at CREST since May 1998. The complete system including integrating sphere and fibre optics was supplied and calibrated by Instruments SA, UK. The integrating sphere faces due south with an inclination of 52° (the latitude at Loughborough) which is also the inclination of adjacent roof mounted PV systems and test cells.

Each characterisation of the spectrum used for this work comprises 141 spectral measurements at 10 nm steps, across the spectral range 300–1700 nm. The integration time for each measurement was chosen to be 0.1 s. Measurements of the incident spectrum were taken every 10 min over the day. The scanning time to complete each run is of the order of 1.5 min. This rather long measurement time does lead to some distortion of the spectrum, especially for days with rapidly moving clouds. However, such distortion will be averaged out to a significant extent by the large number of data sets used.

The measured data were then analysed. Data sets with an overall irradiation of less than $10\,W/m^2$ have been ignored, because they exhibit a poor signal-to-noise ratio. Furthermore, they will contribute insignificantly to the overall energy yield. Global irradiation is calculated by integrating over the whole measured spectrum. Thus, the term global irradiation in this work always refers to the integrated irradiation in the range from 300 to 1700 nm, manifesting the response of the combined detectors. The energy within this spectral range is more than 94% of the standard AM1.5 spectrum; thus, the difference to the overall global irradiation is small. Furthermore, irradiation outside this measurement range certainly is outside the solar cell range.

3. Results and discussion

The effects of the spectral variation on thin film devices have been investigated on the basis of what we call the ‘‘useful fraction’’ for a given technology. This is defined to be the ratio of the observed spectral irradiation in the useful spectral range of the PV device in question to the observed global irradiation. The upper wavelength boundaries for useful irradiation of different technologies were identified from the literature as 1360 nm for CIGS [10], 1100 nm for c-Si [11], 900 nm for CdTe [12] and 780 nm for a-Si [11]. For a-Si, it was decided to consider only single junction a-Si devices. The effect of seasonal spectral variations on multi-junctions cannot be modelled with the simple useful fraction model used here. This is because any shift in the spectrum results in mismatch of the series connected cells in the multi-junction; hence, significant non-linear effects occur which will also impact on the fill factor of a device [13], which is very different to a single junction where the effect is seen mainly in the short circuit current.

There are two main influences on the incident spectrum: air mass and weather. The influence of the weather on the useful fraction is mainly due to increased cloud cover, which can be described, in a simplified manner, through the clearness index k_t. The impact of the two factors is illustrated for a-Si in Fig. 2. In order to generate this graph, the data collected during the measurement period of 30 months was binned. Averaged bin values are presented in Fig. 2 as a surface plot.

It is clear from Fig. 2 that both the air mass and the clearness index have a distinct influence on the spectral composition of the incident radiation, here represented by the useful fraction for the case of a-Si devices. Care is needed, though, as the clearness index and the air mass are not completely independent from each other: a higher air mass will normally result in a lower clearness index, because of the absorption occurring due to the passage of the light through the atmosphere. Fig. 2 also implies there will be a seasonal and daily variation of the useful fraction, as the air mass will be higher in winter and during the morning and evening. It is interesting to note that lower k_t values (i.e. measurements with higher cloud cover) tend to lead to a higher useful fraction. It is known though, that thick cloud cover acts as a filter for IR light and shifts the light towards the blue [14]. In fact, measurements with a very heavy cloud cover appear to have hardly any light beyond the visible range, due

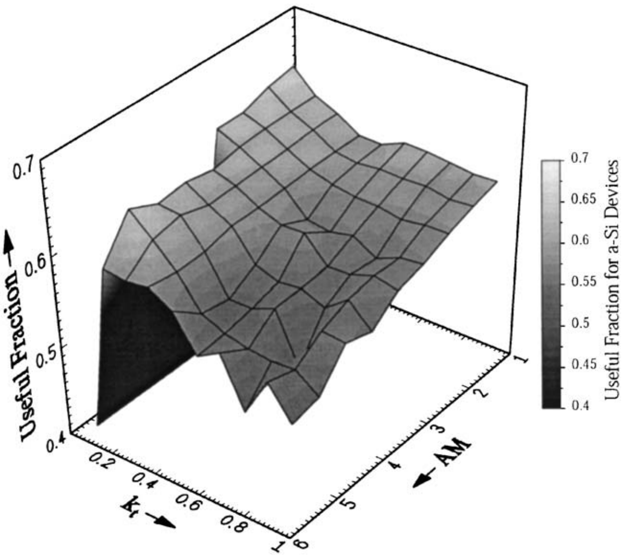

Fig. 2. Influence of the weather and the air mass on the useful fraction for a-Si. The influence of the weather can be expressed using the clearness index k_t. The steep flank for low k_t is exclusively due to a lack of points in this region.

to the diffuse nature of the incident radiation. However, the overall irradiation is also significantly attenuated. It is the magnitude of daily and seasonal variations of this effect that are investigated in what follows. This variation of the useful fraction with air mass does not follow the linear relationship found by Berman et al. [6] for the Negev desert in Israel. The differences in the findings are due to the different climatological conditions and this emphasises the need for this study.

The variation of the useful fraction for different technologies during the course of particular sunny days in winter and summer is presented in Figs. 3 and 4, respectively. In both graphs, the useful fraction and the overall global irradiation is plotted against the local time of the day.

A winter day (Fig. 3) shows a small increase of the useful fraction over the day (ignoring the flanks in the morning and the evening). This is due to the increase of water vapour in the atmosphere and the subsequent improved absorption of radiation at the higher end of the spectrum. It seems to be a wider spread phenomenon, occurring also at other sites. Researchers, e.g. Rüther [15], have reported an increased performance of a-Si systems in the afternoon. The effect reported by Rüther [15] cannot be attributed to any other environmental effect, and thus it appears that spectral effects are the only explanation.

An interesting effect is apparent from the graph of the sunny summer day shown in Fig. 4. The flanks in the morning are reversed, i.e. the useful irradiation does not increase, it appears to decrease in the morning around 6:30 and again in the afternoon at 18:30. These times coincide with the time the sun vanishes behind the input optics, i.e. the incident irradiation changes from a mixture of beam, diffuse and

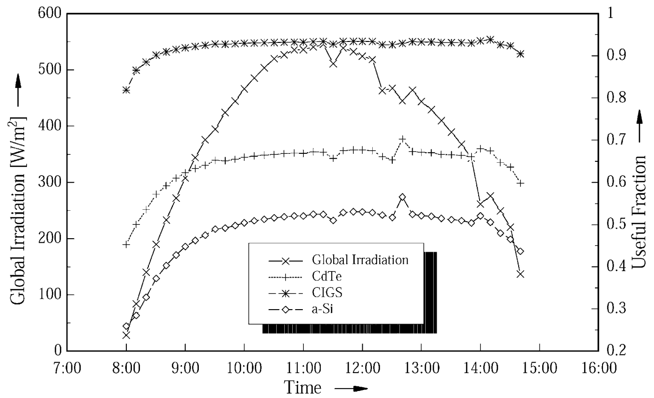

Fig. 3. Variation of useful fraction over a clear winter day. The useful fraction for the different materials is compared with the global irradiation.

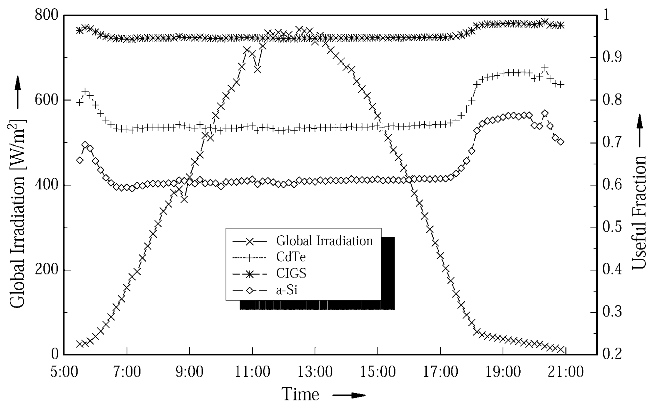

Fig. 4. Variation of useful fraction over a clear summer day. The useful fraction for the different materials is compared with the global irradiation.

albedo to a mixture of diffuse and albedo irradiation only. This has a beneficial effect in the sense that the useful fraction of the incident irradiation increases. Obviously, the blocking of the beam irradiation results in a strong attenuation of the overall radiation so that the energy production of the device will suffer despite the shift.

The impact of the weather can be identified by looking at the variations of the daily integrated useful fraction, as shown for a summer month in Fig. 5 and for a winter month in Fig. 6. There is only a minor weather influence for the summer days, partially due to the fact that the weather was relatively stable during this period. A much more pronounced variation can be observed in December with some very cloudy days showing a higher useful fraction. The average air mass apparent in the course of a month does not vary dramatically. The main difference between the

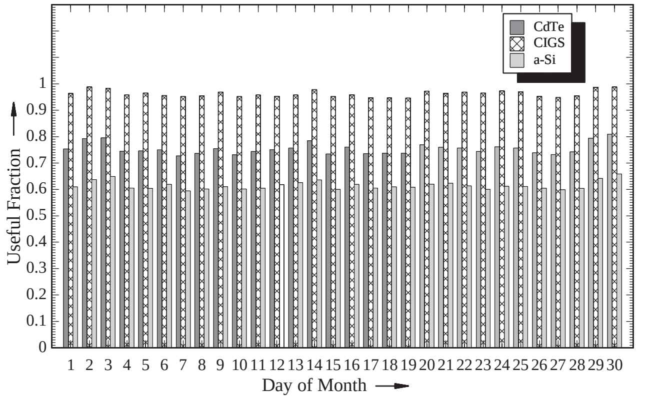

Fig. 5. Variation of the daily useful fraction in June 2000. The graph plots the useful fraction for each day and thus includes the weather dependence of this measure on a day in summer.

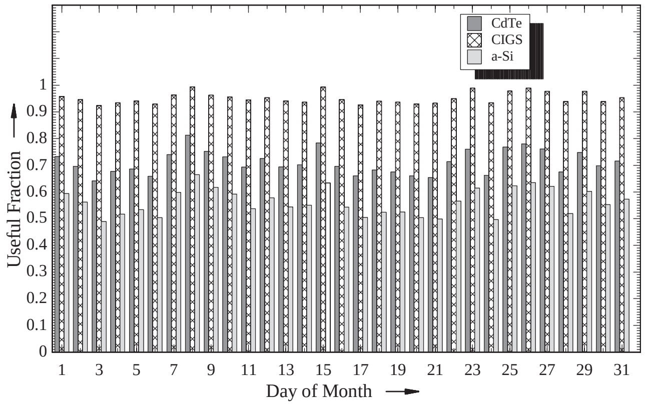

Fig. 6. Variation of the daily useful fraction in December 1999. The graph plots the useful fraction for each day and thus includes the weather dependence of this measure on a day in winter.

sunny and cloudy days is in the absolute irradiation received by any solar collector. In the case of the data presented in Fig. 6, there were days with a maximum global irradiation as low as 45 W/m^2 as well as days with a maximum irradiation of around 600 W/m^2. This large variation in the cloud cover is reflected in the large variations in the useful fractions observed during these different days. Again, this shift in the spectrum could be one of the reasons for the often reported good low light response of a-Si, the photovoltaic material most susceptible to spectral variation.

Finally, the annual effect on thin film devices is investigated. A system measuring the global irradiation, i.e. the data integrated over the complete measurement range of our spectroradiometer (or in conventional monitoring situations, e.g. a thermopile), leads to the results shown in Fig. 7. It is apparent that the spectral effect for CIGS is negligible whilst it is strongest for a-Si, with CdTe being

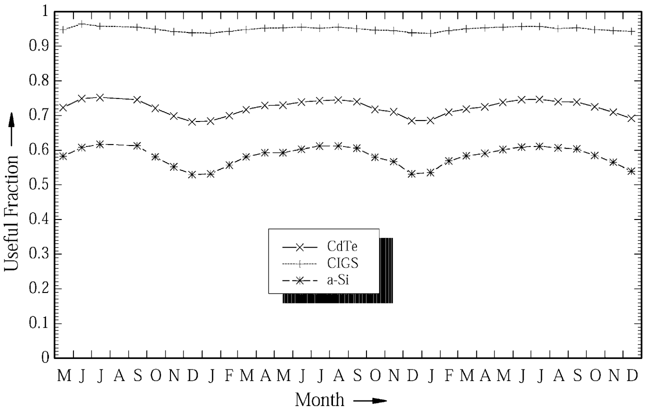

Fig. 7. Seasonal variation of the useful fraction when considering the whole spectrum. The fraction of the irradiation which is in the useful range for the given type of devices is plotted for each month starting May 1998 to December 2000.

somewhere in between. All devices show an improvement of the useful fraction throughout the summer months.

The reason that there are no reports of seasonal variations of the performance except for a-Si devices is due to the other materials being more susceptible to thermal effects. There are two reasons for this: firstly, the band gap of a-Si is larger than the ideal band gap of 1.4 eV calculated for terrestrial applications under AM1.5G [14]. An increase in temperature will decrease the apparent band gap and thus the theoretical efficiency of the devices improves. Second, for good material properties, it can be expected that the effect of the degradation in electronic properties of a-Si devices with increased temperature is attenuated by the device structure, i.e. since they are drift-driven devices, which can cope better with decreased electronic properties. Neither of the other thin film devices has a drift-driven current and thus the effect of increased device temperature (which goes along with increased irradiation levels) will counteract this improved performance.

The magnitude of the variation around the annual average of the useful fraction is plotted in Fig. 8. The effect for CIGS is less than $\pm 1.5\%$ with respect to the annual average. The spectral effect is more pronounced for CdTe, as could be expected from the band gap and the spectral responsivity shown in Fig. 1. The effect ranges from $+4\%$ to -6% around the annual average. The seasonal variation of useful fraction is strongest for a-Si where it ranges from $+6\%$ to -9%. The magnitude of this variation emphasises the importance of considering spectral effects when monitoring photovoltaic devices, it is not always sufficient to monitor global irradiation only, as changes in the spectral composition are not detected. These changes can, as apparent from this analysis, have a significant effect on the overall performance of photovoltaic devices.

There is a difference between measurements taken using the whole spectrum, as for example done with a thermopile, and when using a spectrally selective detector.

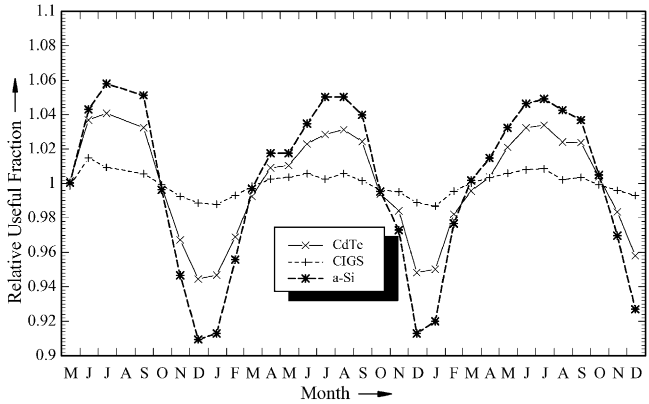

Fig. 8. Relative seasonal variation of the useful fraction when measuring the whole spectrum. The fraction of the irradiation in the useful range for the given devices is plotted for each month starting May 1998 to December 2000.

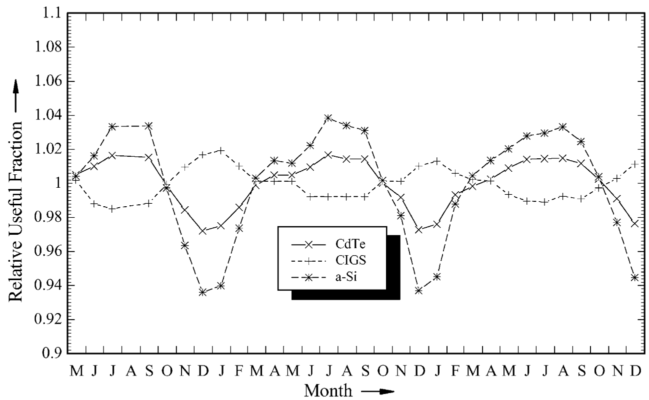

Fig. 9. Relative seasonal variation of the useful fraction when measuring with a silicon detector. The fraction of the irradiation in the useful range for the given type of devices is plotted for each month.

The results which would be obtained when using a silicon detector in isolation are simulated in Fig. 9. Comparing these results with Fig. 8, which depicts a very good approximation of a system monitoring the global irradiation, reveals interesting differences. The spectral effect is inverted for CIGS; thus, the relative efficiency for CIGS would appear to increase in wintertime which is incorrect. Interestingly, the seasonal spectral effect is even stronger than for measurements with a thermopile, only it is inverted with an increased useful fraction in wintertime. This is explained by the fact that c-Si devices are also prone to seasonal variation and are more affected than CIGS. The effect for CdTe and a-Si is less pronounced when measuring with a c-Si detector. The effect is reduced by roughly 30% compared to the variation employing a detector measuring the whole spectrum. Thus, measurements using silicon detectors in isolation may be misleading.

4. Conclusions

It is clear from the presented results that the performance of thin film solar cells will be, to a varying degree, influenced by daily and seasonal variations in the incident solar spectral content. The change in the useful fraction is more influenced by the weather (i.e. cloud cover) than it is by the air mass. In the course of the day, the spectrum shifts towards the blue because of increased absorption due to increased water vapour in the atmosphere and thus the useful fraction tends to increase. The variation of the useful fraction can be used to explain some of the idiosyncratic effects identified for a-Si systems.

On an annual basis, the most affected thin film material is a-Si. It is estimated that the useful fraction for a-Si varies from $+6\%$ to -9% with respect to the annual average. CdTe and CIGS vary in the range of $+4\%$ to -6% and $\pm 1.5\%$, respectively, around the annual average. The effect is only fully apparent if the global irradiation is measured with a thermopile, but the wide acceptance, twin sensor system used in this study provides an acceptable approximation. Measurements with a silicon detector in isolation will not only reduce the apparent magnitude of the effect for CdTe and a-Si, it will even invert the effect for CIGS. The variation of the spectral irradiation could also explain some seasonal effects reported on CdTe, e.g. by del Cueto [16].

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References

[1] G. Kleiss, K. Bücher, A. Raicu, K. Heidler, Performance of thin film solar cells under realistic reporting conditions including degradation effects, in: Proceedings of the 11th European Photovoltaic Solar Energy Conference, Montreux, Harwood Academic Publishers, New York, 1992, pp. 578–581.
[2] N. Martin-Chivelet, Analysis of the spectral factor of different commercial pv modules based on measured data, in: Proceedings of the 14th European Photovoltaic Solar Energy Conference, Barcelona, 1997, pp. 282–283.
[3] S. Nann, Variabilität der spektralen Bestrahlungsstärke der Sonneneinstrahlung und deren Einfluß auf den Wirkungsgrad von Solarzellen, Dissertation, Universität Oldenburg, Oldenburg, 1992.
[4] S. Nann, K. Emery, Spectral effects on PV-device rating, Sol. Energy Mater. Sol. Cells 27 (1992) 189–216.

[5] A. Parretta, A. Sarno, R. Schioppo, M. Zingarelli, L. Cicari, Analysis of loss mechanisms in crystalline silicon modules in outdoor operation, in: Proceedings of the 14th European Photovoltaic Solar Energy Conference, Barcelona, 1997, pp. 242–245.
[6] D. Berman, D. Faiman, B. Fahri, Sinusoidal spectral correction for high precision outdoor module characterization, Sol. Energy Mater. Sol. Cells 58 (1999) 253–264.
[7] F. Fabero, F. Chenlo, Variance in the solar spectrum with the position of the receiver surface during the day for PV applications, in: Proceedings of the 22nd IEEE Photovoltaic Specialists Conference, IEEE Press, New York, 1991, pp. 812–817.
[8] J. Merten, J. Andreu, Clear separation of seasonal effects on the performance of amorphous silicon solar modules by outdoor I/V measurements, Sol. Energy Mater. Sol. Cells 71 (2002) 375–385.
[9] Y. Hirata, T. Tani, Output variation of photovoltaic modules with environmental factors—I. The effect of spectral solar radiation on photovoltaic module output, Sol. Energy 55 (6) (1995) 463–468.
[10] R. Gay, Personal communication, 1996.
[11] K.A. Emery, Solar simulators and I–V measurement methods, Solar Cells 18 (1986) 251–260.
[12] D. Bonnet, Die Cadmium-Tellurid-Dünnschicht-Solarzelle, in: J. Schmid (Ed.), Photovoltaik: Strom aus der Sonne. Technologie, Wirtschaftlichkeit und Marktentwicklung, C.F. Müller, Heidelberg, 1994, pp. 49–64.
[13] R. Rüther, G. Kleiss, K. Reiche, Spectral effects on amorphous silicon solar module fill factors, Sol. Energy Mater. Sol. Cells 71 (2002) 375–385.
[14] M. Green, Solar Cells. Operating Principles, Technology and System Applications, University of New South Wales, Kensington, 1992.
[15] R. Rüther, Demonstrating the superior performance of thin-film amorphous silicon for building-integrated photovoltaic systems in warm climates, in: Solar World Conference 1999, Jerusalem, ISES, 1999, pp. 217–222.
[16] J.A. del Cueto, Review of the field performance of one cadmium telluride module, Prog. Photovoltaics: Res. Appl. 6 (6) (1998) 433–446.