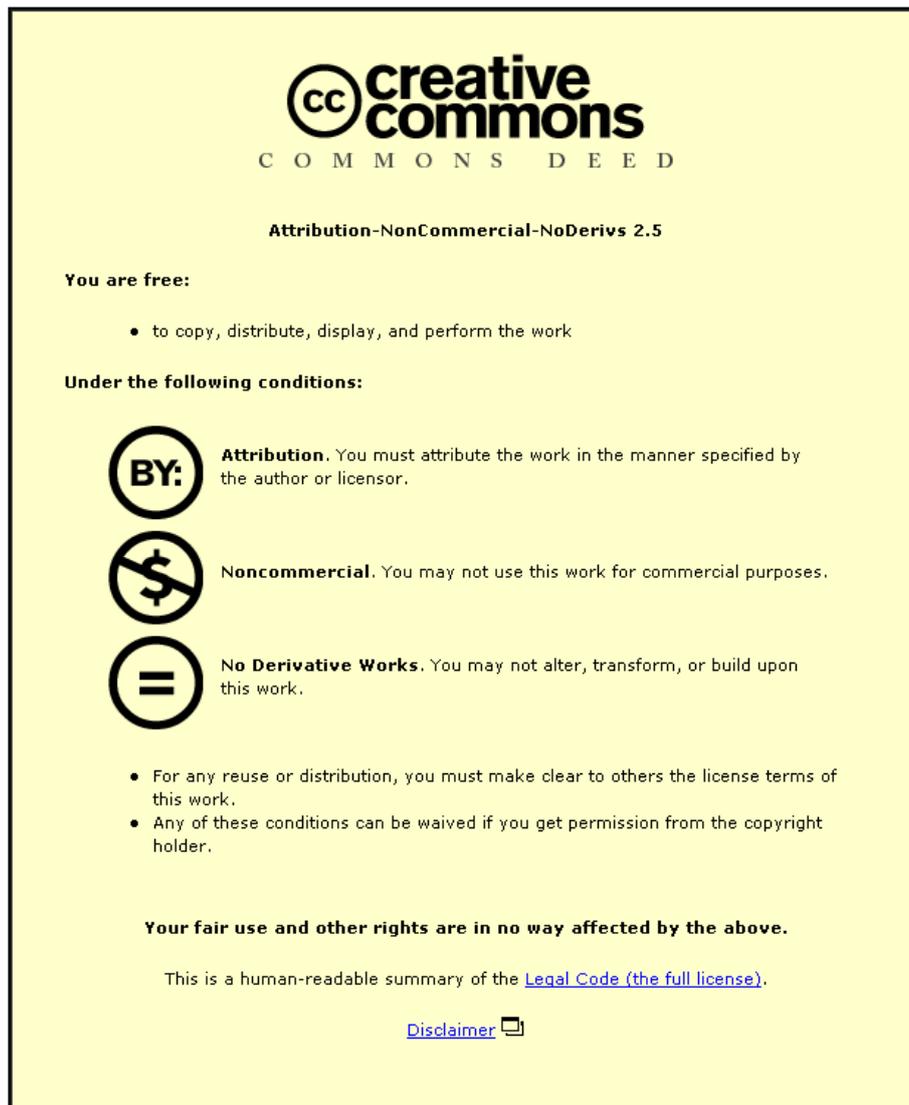




This item was submitted to Loughborough's Institutional Repository (<https://dspace.lboro.ac.uk/>) by the author and is made available under the following Creative Commons Licence conditions.



**CC creative commons**  
COMMONS DEED

**Attribution-NonCommercial-NoDerivs 2.5**

**You are free:**

- to copy, distribute, display, and perform the work

**Under the following conditions:**

**BY:** **Attribution.** You must attribute the work in the manner specified by the author or licensor.

**Noncommercial.** You may not use this work for commercial purposes.

**No Derivative Works.** You may not alter, transform, or build upon this work.

- For any reuse or distribution, you must make clear to others the license terms of this work.
- Any of these conditions can be waived if you get permission from the copyright holder.

**Your fair use and other rights are in no way affected by the above.**

This is a human-readable summary of the [Legal Code \(the full license\)](#).

[Disclaimer](#) 

For the full text of this licence, please go to:  
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

## DUST EFFECT ON PV MODULES

H. Qasem<sup>\*1</sup> T. R. Betts<sup>1</sup>, H. Müllejans<sup>2</sup>, H. AlBusairi<sup>3</sup>, R. Gottschalg<sup>1</sup>.

<sup>1</sup>Centre for Renewable Energy Systems Technology (CREST), Department of Electronic and Electrical Engineering, Loughborough University, Leicestershire, LE11 3TU, UK.

Phone: +44(0)1509 63 5337, Fax: +44(0)1509 63 5301 E-mail: H.Qasem@lboro.ac.uk

<sup>2</sup>European Commission, Joint Research Centre, Institute for Energy, Renewable Energy Unit, I-21027 Ispra (VA), Italy

<sup>3</sup>Kuwait Institute for Scientific Research (KISR) Building and Energy Technologies Department, P.O Box 24885 Safat 13109, Kuwait

### ABSTRACT

This paper investigates the effect of dust on photovoltaic (PV) modules with respect to dust concentration, wavelength and spectral transmittance. Dust samples were collected from Kuwait in the form of raw dust and accumulated dust on sample glass at different tilt angles. The spectral transmittance was measured in the Centre for Renewable Energy Systems Technology (CREST) laboratory with a spectrophotometer. Spectral transmittance variation was identified for samples at different tilted positions, where the worst case was presented at a tilt angle of 30° with a non uniformity of 4.4% in comparison to 0.2% for the 90° tilt between the top, middle and bottom. The effect of this on PV is investigated by calculating a modified spectral response for different technologies using spectral response data measured by the European Solar Test Installation (ESTI). The measured data showed a faster rate of decrease in transmittance at wavelengths <570 nm. This affects wide band-gap technologies more than crystalline silicon technologies and especially amorphous silicon which showed a 33% reduction in the spectral photocurrent when a dust concentration of 8.5 mg/cm<sup>2</sup> was applied. In comparison, the crystalline silicon and copper indium gallium diselenide (CIGS) technologies showed 28.6% and 28.5% reductions at the same dust density.

### I. INTRODUCTION

Dust is one of the natural elements available in the environment. The variation in dust particles' sizes and compositions depends on the location [4]. In some regions, dusty weather conditions tend to be more severe than in others. It causes deterioration in visibility during dusty days [1-2]. Also, dust tends to settle down creating a fine layer of accumulated dust on any exposed surface. It has been reported that different parameters support the accumulation of dust such as gravitational forces, wind speed, wind direction, electrostatic charges and the wetness of the surface [3]. Out of those parameters, the most dominating effects are the gravitational effect, particle size and wind direction [4]. Slow wind will increase the deposition of dust, while fast wind speed will help remove dust if wind is incident in an appropriate direction [3, 5]. The random accumulation of dust on the PV module surface

area can produce spots with varying concentration of dust particles, as illustrated in Figure 1. These spots vary in shape, location and concentration density. The variation in dust accumulation in any place can lead to different transmittance of light into the module, thus leading to small random areas on the PV module with partial shading from the solar radiation.

It has been reported that falling dust has a direct effect of reducing the performance of solar PV modules [2-12]. Accumulated and airborne dust reduces the amount of solar radiation incident on the surface of a PV module [4]. Goosens and Van Kerschaever [5] provide a relation between airborne dust, accumulated dust and the reduction in PV cell short circuit current. Using a wind tunnel experiment, they showed that there is an aerodynamic relation between airborne dust, accumulated dust and the reduction in PV power output [9]. Others have reported a relation between dust particle size, particle distribution, tilt angle and the reduction in transmittance of solar radiation [4, 6, 8]. In general, all these publications show a reduction in short circuit current with increase in accumulated dust concentration.



Figure 1: Accumulated dust on different PV modules installed in Kuwait.

Most of the work reported in relation to dust was with regard to the module direct output performance. Some papers have suggested casual cleaning, static devices and optimization for tilt angle according to the dust information in the region [3, 10-12]. Others have reported special glass coating that promotes self cleaning [13]. The cost effectiveness of these methods is not yet known, and require further investigation before deciding on the right method. On the other hand, relatively little work has been done in identifying the variation of dust concentration on the tilted PV module and the effect of dust on different PV technologies. In this paper, a relation between spectral transmittance and dust concentration is established which will be used to

identify the variation of dust concentration on tilted modules and the effect of dust on different PV technologies through the modification of the effective spectral response.

## II. METHODOLOGY

Dust samples were collected using a collecting vessel that was left outdoors for a number of days in a dusty season in Kuwait. The collected dust was deposited on 2.0cm x 2.0cm area using a 5.0cm x 5.0cm Soda Lime glass with a thickness of 1.0 mm. The deposition of dust was done by free fall from 1.0 m height using a cylindrical tube to minimize the effect of wind currents in the lab. The weights of the samples were measured using a Mettler AE260 Delta range weight balance with sensitivity of 0.1 mg. Finally, the samples were encapsulated and spectral transmittance of the sample was measured using a Cary spectrophotometer. The transmittance of a clean none-dusty encapsulated glass sample was measured and used to correct the dusty samples measurements with taking into account avoiding short wavelengths < 300nm due to the filtering property of Soda Lime glass.

To investigate the effect of tilt angle, a number of 4.0cm x 4.0cm heat tempered glass samples were installed in a dusty environment in Kuwait for a period of one month. The samples were placed facing south, with tilt angles of 0°, 15°, 30°, 45°, 60° and 90°. The samples were then encapsulated and divided into three sections, top, middle and bottom. The transmittance of each sample at each section was measured using a Cary spectrophotometer. The spectral transmittance data obtained from the dust samples were then used to modify measured spectral response data from ESTI for 9 crystalline silicon (c-Si), 3 amorphous silicon (a-Si), 2 copper indium gallium diselenide (CIGS) and one cadmium telluride (CdTe) modules. The modified data are used to correlate the effect of dust on different PV technologies.

## III. RESULTS AND DISCUSSION

### A. Sediment Characterization

The dust sample was collected in Kuwait during the month of May 2010 for a period of 30 days. The sand grain sizes were then analysed using an Olympus CX41 microscope to find the grain size distribution. This was characterised using the Phi value, which uses  $(-\log_2 \text{Diameter})$  as the sorting criterion. The collected dust sample size distributions are shown in Figure 2. The grain size distribution was found to be of silt that was distributed between coarse, medium and fine silt as shown in Table 1. The majority of the silt grains were of slate, whereas the bigger grains were quartz.

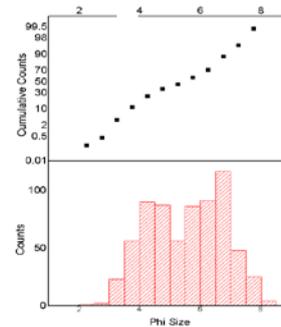


Figure 2: A histogram and a probability distribution of the counted samples

$\Phi$	% of the total sample	Cumulative weight percent	Grain type
0.0 - 1.0	0.0	0.0	Coarse grained
1.0 - 2.0	0.0	0.0	Medium grained
2.0 - 3.0	0.6	0.0	Fine grained
3.0 - 4.0	11.4	28.4	Very fine grained
4.0 - 5.0	25.8	40.7	Coarse silt
5.0 - 6.0	20.7	16.4	Medium silt
6.0 - 7.0	30.2	11.7	Fine silt
7.0 - 8.0	10.7	2.4	Very fine silt
< 8.0	0.6	0.1	Clay

Table 1: Dust grain distribution and size types

### B. Dust Concentration

The dust sample transmittances were measured with a Cary spectrophotometer over a wavelength range of 300nm to 1200nm as shown in Figure 3. It is worth noting that any values under 300nm or higher than 1200nm are beyond our scope since the spectral response wavelengths used by most materials used in PV technologies are within the 300 nm – 1200 nm band. In the region between 300 nm - 570 nm, it was noted that transmittance dropped at a faster rate than that at > 600nm as shown in Figure 3. The discontinuity in the transmittance curve happens during the lamp change in the spectrophotometer and it can be considered as measurement artifact. At dust concentration > 38 mg/cm<sup>2</sup> the effect of wavelength becomes minimal especially in the visible range. Where at wavelength > 570 nm the variation between concentration-transmittance curves is 2.5% on average where at wavelength < 570 nm the

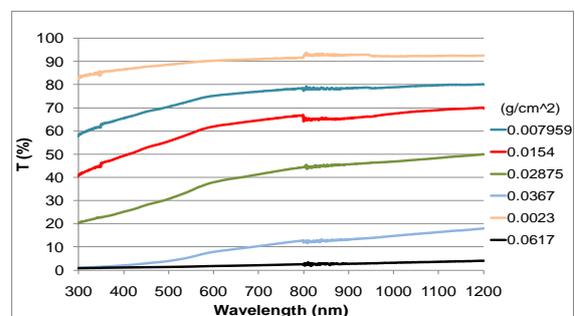


Figure 3: Spectral transmittance curves for different dust concentration samples.

average percentage difference is 11%. So in this prospective it can be said that at shorter

wavelength, dust effect is more severe than at longer wavelengths.

### C. Tilt Angle

The variation of dust accumulation on tilted surfaces was shown in the spectral transmittance data obtained from measuring the dust samples collected in Kuwait in the period from 9/9/2009-6/11/2009. The dust samples were encapsulated and spectral transmittance was measured at three different areas, top, middle and bottom see Figure 4.

Two general trends were observed in the spectral transmittance data shown in Figure 4. The first trend shows that with increased tilt angle, dust accumulation decreases, this can be explained as gravity affecting dust samples more where tilt angle increases. The second trend is shown more clearly in Table 2, where transmittance decreases on tilted samples toward the bottom. The 90° sample showed only a non-uniformity of 0.21%, in comparison to the 30° which showed 4.39% non-uniformity between the top, middle and bottom. The 0° showed a higher variation than that of 15°. This can be attributed to the higher dust concentration of the 0° sample which made it more sensitive to environmental effects such as wind direction in comparison to the tilted samples.

0°	15°	30°	45°	60°	90°
1.98	1.01	4.39	1.00	0.73	0.21

Table 2: Non uniformity of transmittance at different tilt angles (%)

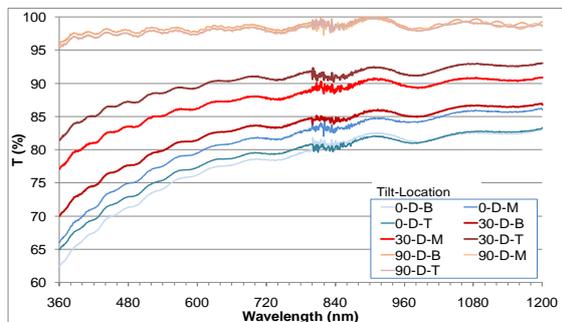


Figure 4: Spectral transmittance curves for different tilted samples at 0, 15, 30, 45, 60 and 90°.

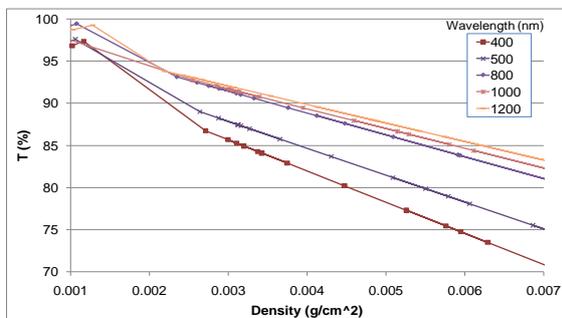


Figure 5: Transmittance concentration curves obtained by fitting the spectral transmittance curves for the tilted samples into measured dust concentration curves obtained in section III-B.

The variation of the transmittance in the tilted sample is clearly due to the variation of dust concentration at different locations in the sample. To identify the dust concentration, the spectral transmittance data for the tilted sample were fitted between the data measured in section II-B in the range of 2-9 mg/cm<sup>2</sup> of dust concentration.

The obtained concentration transmittance curves for the tilted samples are shown in Figure 5. The fitted dust concentration values shown in Table 3 agree with the results obtained in Table 2 where the sample tilted at 30° showed the worst case variation in comparison to the 90° between top (T), middle (M) and bottom (B) sections of the sample.

	0° (mg/cm <sup>2</sup> )			15° (mg/cm <sup>2</sup> )			30° (mg/cm <sup>2</sup> )		
	B	M	T	B	M	T	B	M	T
AVG	7.1	6.0	6.9	4.9	4.2	4.8	5.4	3.6	2.6
MIN	8.5	7.7	7.8	6.2	5.6	6.1	6.7	4.9	3.8
MAX	6.4	5.2	6.5	4.0	3.6	4.3	4.9	3.0	2.1
STD	0.5	0.6	0.3	0.6	0.5	0.4	0.4	0.4	0.4
	45° (mg/cm <sup>2</sup> )			60° (mg/cm <sup>2</sup> )			90° (mg/cm <sup>2</sup> )		
	B	M	T	B	M	T	B	M	T
AVG	2.3	2.9	2.6	2.5	2.5	2.0	0.6	0.4	0.4
MIN	3.3	4.1	3.8	3.5	3.4	3.1	0.9	0.8	0.7
MAX	1.8	2.5	2.2	2.1	2.1	1.6	0.1	0.1	0.1
STD	0.3	0.4	0.4	0.3	0.3	0.3	0.2	0.2	0.2

Table 3: Dust concentration (mg/cm<sup>2</sup>) values in this table are obtained from the fitted transmittance curve data in Figure 5

### D. Spectral Effect

Spectral response data for different PV technologies supplied by ESTI were modified with the different spectral transmittance curves obtained in sections III-B and III-C. The modified curves show a variation between different technologies with regard to the same spectral transmittance dust curves as shown in Figure 6, Figure 7 and Table 4. In Figure 6, 9 samples of c-Si modules' spectral response data were multiplied with 4 dust spectral transmittance curves while Figure 7 shows the same transmittance curves applied to a-Si, CIGS and CdTe PV modules. The spectral photocurrents shown in Table 4 were obtained by integrating the area under the product of the AM 1.5 spectrum [14] and the spectral responses in Figure 6 & Figure 7.

From Table 4, we can see that a-Si and CdTe technologies are affected more than the c-Si and CIGS modules when they are covered with dust. This can be correlated to the high band gap of the most affected modules which have an effective spectral response range between 300 nm to 800 nm where spectral transmittance dust curve rate of transmittance decreases significantly.

Concentration (mg/cm <sup>2</sup> )	a-Si (%)	CIGS (%)	CdTe (%)	c-Si (%)
8.5	-33.0	-28.5	-30.1	-28.6
28	-66.0	-59.6	-61.9	-59.6
38	-77.4	-70.6	-73.1	-70.6
61	-98.4	-97.8	-98.1	-97.8

Table 4: Percentage difference in photocurrent between clean module data and data with dust transmittance applied.

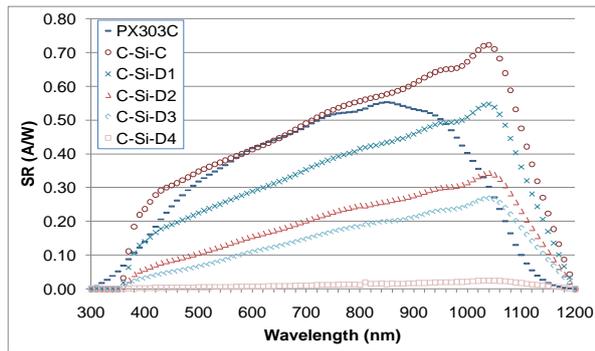


Figure 6: Spectral response data for 9 c-Si modules corrected for 4 different spectral transmittance dust curves, D1=8.5mg/cm<sup>2</sup>, D2=28 mg/cm<sup>2</sup>, D3=38 mg/cm<sup>2</sup> and D4=61 mg/cm<sup>2</sup>.

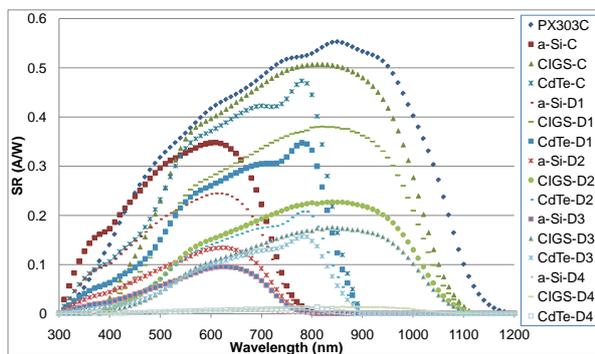


Figure 7: Spectral response data for thin-film modules.

#### IV. CONCLUSION

The relation between dust concentration and spectral transmittance shows that with high dust concentration (>38 mg/cm<sup>2</sup>) the variation with wavelength becomes minimal. Another trend shows that at dust concentration < 38 mg/cm<sup>2</sup> the spectral transmittance curve shows two regions, >570 nm spectral transmittance data showed a very minimal change in transmittance. Where the second region at wavelength <570 nm showed a faster drop at transmittance

The effect of tilt angle is directly related to the amount of dust density variation on the surface. The 90° tilt angle showed the least variation of dust accumulation of 0.2 mg/cm<sup>2</sup> due to the fact that gravity affects it the most and supports the process of dust removal over time. The sample tilted at 30°, which is the optimal tilt angle for PV modules in Kuwait regarding sun position, showed the highest variation of dust accumulation of 1.87 mg/cm<sup>2</sup> with most of dust concentration toward the bottom.

Dust contributes to the reduction of PV module output by reducing the incident irradiance in a spectrally selective manner. This can be seen in the effect on the spectral response data when the dust spectral transmittance curves are applied. This effect is not the same magnitude for all types of PV technology because the spectral

transmittance affects various spectral response shapes differently. The effect is worse for PV modules with higher band gap such as a-Si and CdTe technologies which showed 33% reduction in the spectral response when a concentration of 8.5 mg/cm<sup>2</sup> of dust was applied. In comparison, c-Si and CIGS technologies showed 28.6% and 28.5 reductions, respectively, under the same dust density.

#### REFERENCES

- [1] M. I. Safar and Kuwait. Meteorological Dept. Climatological Section., *Frequency of Dust in Day-Time Summer in Kuwait*. Kuwait: Directorate General of Civil Aviation, Meteorological Department, Climatological Section, 1980.
- [2] S. Biryukov, "An experimental study of the dry deposition mechanism for airborne dust," *J. Aerosol Sci.*, vol. 29, pp. 129-139, 2, 1998.
- [3] M. Mani and R. Pillai, "Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 3124-3131, 12, 2010.
- [4] H. K. Elminir, A. E. Ghitas, R. H. Hamid, F. El-Hussainy, M. M. Beheary and K. M. Abdel-Moneim, "Effect of dust on the transparent cover of solar collectors," *Energy Conversion and Management*, vol. 47, pp. 3192-3203, 11, 2006.
- [5] D. Goossens and E. Van Kerschaver, "Aeolian dust deposition on photovoltaic solar cells: the effects of wind velocity and airborne dust concentration on cell performance," *Solar Energy*, vol. 66, pp. 277-289, 7, 1999.
- [6] E. Asl-Soleimani, S. Farhangi and M. S. Zabihi, "The effect of tilt angle, air pollution on performance of photovoltaic systems in Tehran," *Renewable Energy*, vol. 24, pp. 459-468, 11, 2001.
- [7] H. Pang, J. Close and K. Lam, *Study on Effect of Urban Pollution to Performance of Commercial Copper Indium Diselenide Modules*. NEW YORK; 345 E 47TH ST, NEW YORK, NY 10017 USA: IEEE, 2006.
- [8] M. S. El-Shobokshy and F. M. Hussein, "Effect of dust with different physical properties on the performance of photovoltaic cells," *Solar Energy*, vol. 51, pp. 505-511, 12, 1993.
- [9] D. Goossens, Z. Y. Offer and A. Zangvil, "Wind tunnel experiments and field investigations of eolian dust deposition on photovoltaic solar collectors," *Solar Energy*, vol. 50, pp. 75-84, 1, 1993.
- [10] R. Hammond, D. Srinivasan, A. Harris, K. Whitfield and J. Wohlgemuth, "Effects of soiling on PV module and radiometer performance," *Photovoltaic Specialists Conference, 1997. , Conference Record of the Twenty-Sixth IEEE*, pp. 1121-1124, 1997.
- [11] J. M. Rolland, S. Astier and L. Protin, "Static device for improving a high voltage photovoltaic generator working under dusty conditions," *Solar Cells*, vol. 28, pp. 277-286, 5, 1990.
- [12] A. B. Rabii, M. Jraidi and A. S. Bouazzi, *Investigation of the Degradation in Field-Aged Photovoltaic Modules*. Tokyo; Tokyo Univ Agriculture and Technology; Tokyo, Koganei 184-8588, Japan: WCPEC-3 Organizing Committee, 2003.
- [13] S. Bruynooghe, S. Spinzig, M. Fliedner and G. J. HSU, "Realization of High Performance AR-coatings with Dust- and Water-Repellent Properties," *Vakuum in Forschung Und Praxis*, vol. 20, pp. 25-29, 2008.
- [14] International Electrotechnical Commission, "Photovoltaic devices — part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data," IEC International Standard, Geneva, Switzerland, 60904-3, edition 2.0 2008.