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Performance of Photovoltaics Under Actual Operating Conditions

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1. Introduction

Amongst the various renewable energy sources, photovoltaic (PV) technologies that convert sunlight directly to electricity have been gaining ground and popularity, especially in countries with high solar irradiation. Over the past years PV has shown rapid development and a wide variety of new technologies from different manufacturers have emerged. For each PV module type, manufacturers provide typical rated performance parameter information which includes, amongst others, the maximum power point (MPP) power, efficiency and temperature coefficients, all at standard test conditions (STC) of solar irradiance 1000 W/m^2, air mass (AM) of 1.5 and cell temperature of 25 °C. As this combination of environmental conditions rarely occurs outdoors, manufacturer data-sheet information is not sufficient to accurately predict PV operation under different climatic conditions and outdoor PV performance monitoring and evaluations are necessary.

The objective of this chapter is to provide an overview of different PV technologies ranging from crystalline silicon (c-Si) to thin-film and concentrators. Subsequently, a summary of the main outdoor evaluation performance parameters used to describe PV operation and performance is outlined. An overview of the effects of different environmental and operational factors such as solar irradiance, temperature, spectrum and degradation is also provided along with the results of previously published research efforts in this field. In the last section of the chapter, the installed PV and data acquisition infrastructure of a testing facility in Cyprus is presented and a thorough analysis of the climatic conditions and the performance of different grid-connected PV technologies that have been installed side-by-side and exposed to warm climatic conditions, typical of the Mediterranean region are given.

2. Overview of photovoltaic technologies

Over the last twenty years, the PV industry showed annual growth rates between 40 % and 80 %, proving its strength and potential to become a major worldwide power generation source (Joint Research Centre [JRC], 2010). The enormous potential of PV is also evident by the fact that the existing global energy demands could be met by over 10,000 times, had the surface area of the Earth been covered with currently available PV technologies (European

Photovoltaic Industry Association [EPIA] & Greenpeace, 2011). Nowadays, the threat of climate change and the continuous rise of oil prices have added more pressure for the integration of renewable technologies for energy production, with PV drawing considerable attention. More specifically, at the end of 2008 the cumulative worldwide installed PV capacity was approximately 16 GW (EPIA, 2011). The market growth continued throughout 2009, despite the international economic crisis and according to the European Photovoltaic Industry Association (EPIA) the installed capacity was 23 GW while in 2010, the accumulated capacity reached 40 GW worldwide with more than 50 TWh of electricity production per year (EPIA, 2011). The largest PV market was the European Union (EU) with more than 13 GW installed in 2010 and a total installed capacity of almost 30 GW as of 2010 (EPIA, 2011).

A wide range of PV technologies now exist that include mono-crystalline silicon (mono-c-Si), multi-crystalline silicon (multi-c-Si), thin-film technologies of amorphous silicon (a-Si), micromorph (microcrystalline/amorphous silicon), cadmium telluride (CdTe), copper-indium-gallium-diselenide (CIGS), concentrating PV (CPV) and other emerging PV technologies. Each technology is mainly described and classified according to the material used, manufacturing procedure, efficiency and cost.

Amongst the various existing PV technologies, c-Si is the most developed and well understood due to mainly its use in the integrated circuit industry. In addition, silicon is at present the most abundant material found in the earth's crust and its physical properties are well defined and studied. C-Si dominates the PV technology market with a share of approximately 80 % today (EPIA & Greenpeace, 2011). The type of c-Si technology depends on the wafer production and includes mono-c-Si, multi-c-Si, ribbon and sheet-defined film growth (ribbon/sheet c-Si).

The main characteristic of mono-c-Si is its ordered crystalline structure with all the atoms in a continuous crystalline lattice. Mono-c-Si technologies are highly efficient but are at the same time the most expensive amongst the flat-plate existing PV technologies mainly because of their relatively costly manufacturing processes. Over the past years, manufacturing improvements of c-Si PV technology have focused on the decrease of wafer thickness from 400 μm to 200 μm and in parallel the increase in area from 100 cm^2 to 240 cm^2. The most important limitation of this technology is the cost of the silicon feedstock which renders the material cost relatively high, particularly as the silicon substrate must have a thickness of approximately 200 μm to allow the incident light to be absorbed over a wide range of wavelengths. Despite the high material cost, this technology has remained competitive due to several manufacturing improvements such as enhancements in wire cutting techniques that have reduced the wafer thickness and also the production of kerf-less wafers. Recently, Sunpower announced an efficiency of 24.2 % for a large 155 cm^2 silicon cell fabricated on an n-type Czochralski grown wafer (Cousins et al., 2010).

The fact that mono-c-Si modules are produced with relatively expensive manufacturing techniques initiated a series of efforts for the reduction of the manufacturing cost. Such a cost improvement was accomplished with the production of multi-c-Si PV which can be produced by simpler and cheaper manufacturing processes. Multi-c-Si solar cell wafers consist of small grains of mono-c-Si and are made in a number of manufacturing processes. The substrate thickness is approximately 160 μm while attempts are being made to lower the thickness even more. In general, multi-c-Si PV cells are cheaper compared to mono-c-Si as they are produced in less elaborate manufacturing process, at the expense of slightly lower efficiencies. The lower efficiency is attributed to recombination at the grain boundaries within the multi-c-Si structure. Nonetheless, multi-c-Si currently has the largest PV market share.

Ribbon silicon is another type of multi-c-Si technology which is produced from multi-c-Si strips suitable for the photovoltaic industry. In the manufacturing process of this technology, high temperature resistant wires are pulled through molten silicon to form a ribbon which is subsequently cut and processed in the usual manner to produce PV cells. An advantage of this technology is that the production costs are lower than other c-Si technologies, while the efficiency and quality of the cells remain the same as other multi-c-Si technologies but lower than mono-c-Si.

The main incentive for the development of thin-film technologies has been their cheap production cost compared to the c-Si counterparts. Over the past years, thin-film technologies have shown very encouraging development as the global production capacity has reached around 3.5 GW in 2010 and is expected to reach between 6 - 8.5 GW in 2012 (EPIA, 2011). Amongst the many thin-film technologies some of the most promising are CdTe, a-Si, micromorph tandem cells (a-Si/μc-Si) and CIGS. The rapid growth and importance of thin-film PV is further highlighted by the fact that the world's first PV manufacturer to exceed the 1 GW/year production rate and hence to capture 13 % of the global market was First Solar, a manufacturer of thin-film CdTe modules, in 2009 (Wolden et al., 2011). Specifically, CdTe has grown from a 2 % market share in 2005 to 13 % in 2010 (EPIA & Greenpeace, 2011).

Amorphous silicon has been on the PV market longer than other thin-film technologies and this has allowed researchers and manufacturers to understand several aspects of its behavior. This technology was first commercialized in the early 1980s and since then has increased gradually in efficiency. The manufacturing of a-Si technologies is dominated by deposition processes such as plasma enhanced chemical vapor deposition (PECVD) and thus large area, flexible and cheap substrates such as stainless steel and thin foil polymer can be used (Shah et al., 1999). In comparison to mono-c-Si, a-Si PV cells have no crystalline order leading to dangling bonds which have a severe impact on the material properties and behavior. Another important material limitation arises from the fact that this technology suffers from light-induced degradation, also known as the Staebler–Wronski effect (SWE), which describes the initial performance decrease when a-Si modules are first exposed to light (Staebler & Wronski, 1977). In general, this effect has been minimized by employing double or triple-junction devices and developing micromorph tandem cells, which is a hybrid technology of c-Si and a-Si. An important advantage of a-Si is the high absorption coefficient, which is approximately 10 times higher than c-Si therefore resulting in much thinner cells.

The concept of micromorph (microcrystalline/amorphous silicon) tandem cells was introduced to improve the stability of a-Si tandem cells. The structure of a micromorph device includes an a-Si cell which is optimized with the application of a micro-crystalline silicon (μc-Si) layer of the order of 2 μm onto the substrate. The application of the μc-Si layer assists the device in increasing its absorption in the red and near infrared part of the light spectrum and hence increases the efficiency by up to 10 % (EPIA & Greenpeace, 2011). Oerlikon Solar developed and announced recently a lab cell with 11.9 % stabilized efficiency (Oerlikon Solar, 2010).

Another type of thin-film technology is CdTe, which is a II-VI semiconductor with a direct band gap of 1.45 eV. The high optical absorption coefficient of this technology further allows the absorption of light by a thin layer, as it absorbs over 90 % of available photons in a 1 μm thickness, hence films of only 1 - 3 μm are sufficient for thin-film solar cells (Ferekides & Britt, 1994). PV devices of CdTe first appeared in the 1960s (Cusano, 1963) but the technological development outbreak came in the early 1990s when efficiencies approached levels of commercial interest (Britt & Ferekides, 1993). CdTe technology is a front-runner amongst thin-film PV technologies due to the fact that it can be produced relatively cheaply and module efficiencies have reached 12.8 % (Green et al., 2011). So far, the achieved efficiency of this technology is lower compared to c-Si, but higher than triple-junction a-Si. In comparison to a-Si, the CdTe PV technology does not show initial degradation. In addition, the power is not affected to the same extent by temperature variations as c-Si based technologies (Doni et al., 2010). On the other hand, concerns have been raised related to the availability of tellurium (Te) and the environmental impact of cadmium (Cd). These concerns have been addressed by Fthenakis et al. (Fthenakis, 2004, 2009; Fthenakis et al., 2005, 2008). In order to minimize the environmental impact of this technology, a recycling process for used modules has been introduced (Meyers, 2006) and the rest of the PV industry is currently moving in this direction (PVCYCLE program).

The properties of several I-III chalcopyrite compounds are also suitable for photovoltaic applications and amongst them the most promising include copper-indium-diselenide ($CuInSe_2$) often called CIS, copper-gallium-diselenide ($CuGaSe_2$) called CGS, their mixed alloys copper-indium gallium-diselenide ($Cu(In,Ga)Se_2$) called CIGS and copper-indium-disulfide ($CuInS_2$). The first PV devices of copper chalcopyrite appeared in 1976 (Kazmerski et al., 1976) and since then it was not until the early 1990s that rapid improvements increased efficiencies to over 16 % (Gabor et al., 1994). Even though the commercial production of CIGS began in 2007, there are now a number of companies with 10 - 30 MW/year capacities (Wolden et al., 2011). Efficiencies continued to improve exceeding the 20 % threshold (Green et al., 2011) and establishing this technology as the efficiency leader amongst existing thin-film technologies. The main advantage of CIGS over other existing thin-film PV technologies is its high efficiency. In addition, CIGS modules have a performance very similar to that of c-Si technologies but have lower thermal losses as the power temperature coefficient is lower. A previous study has also shown that CIGS PV modules show an increase in power output after exposure to sunlight, a phenomenon known as light induced annealing (LIA) (Jasenek et al., 2002). On the other hand, the fabrication process of this technology is more complicated than in other technologies and as a result manufacturing costs are higher. In addition, costs may be also affected by the limited availability of indium and the difficulty in up scaling from cell to large area modules.

An emerging application of PV is in concentrator photovoltaics (CPV) systems. CPV technologies are gaining in popularity as they offer several advantages over established PV technologies. CPV make use of relatively inexpensive optical devices, such as lenses or mirrors to focus light from an aperture onto a smaller active area of solar cell. In doing so, light is 'concentrated' to higher intensities than ordinary sunlight, and less PV cell material is required for a given output. This brings several benefits: the total cost of the system can be reduced; higher system efficiencies are possible due to the increased solar flux intensities; higher efficiency cells can be used without incurring great cost; and demand for

semiconductor materials can be reduced, thereby easing supply restrictions on these materials and facilitating reductions in market price. The target installation locations for CPV are predominantly in the world's sunbelts. This is because CPV systems utilize the direct normal irradiation (DNI) component of sunlight, which makes areas with high annual irradiance such as southern US states, Australia, the Middle East, North Africa and Mediterranean regions the prime target areas for this technology. Today a worldwide total of approximately 35 MW of CPV have been installed. Recent activity, particularly in the US market, has resulted in a rapid increase in projected installed capacity, which will total approximately 400 MW worldwide by the end of 2012 (Greentechmedia [GTM], 2011). Although CPV offers a promising route to lower solar electricity prices, it remains a strong technical challenge. In the last few years, the dramatic fall in the cost of conventional flat-plate PV systems has raised the bar on entry into the energy market for CPV. Systems operating above 5-fold concentration require some form of solar tracking, and most CPV systems require highly accurate tracking, which contributes significantly to the cost of the system, and reduces performance reliability. Also, as of yet there is little long-term experience of large CPV installations in operation and therefore the cost of electricity produced over the system lifetime is hard to predict. A number of CPV manufacturers are aiming to increase their competitiveness by setting a system efficiency of 30 % as a milestone to break into the solar power market, and the present trajectory of CPV cell efficiencies makes this increasingly feasible in the near future.
Table 1 summarizes the key characteristics of typical commercial PV modules.

Technology	Material thickness (μm)	Area (m^2)	Efficiency (%)	Surface area for 1 kW_p system (m^2)
Mono-c-Si	200	1.4 - 1.7 (typical)	14 - 20	~7
Multi-c-Si	160	1.4 - 1.7 (typical) 2.5 (up to)	11 - 15	~8
a-Si	1	~1.5	4 - 8	~15
a-Si/μc-Si	2	~1.4	7 - 9	~12
CdTe	~1 - 3	~0.6 - 1	10 - 11	~10
CIGS	~2	~0.6 - 1	7 - 12	~10

Table 1. Typical commercial PV module characteristics.

Costs decrease with volume of production and prices for large systems decreased as low as 2.5 €/W_p in some countries in 2010 (EPIA, 2010), while the cost of producing electricity using PV has dropped reaching an average generation cost of 15 c€/kWh in the southern parts of the EU (EPIA & Greenpeace, 2011), demonstrating clearly that PV electricity production has already reached grid-parity in some parts of the world such as southern Europe.

3. Photovoltaic performance parameters

An essential requirement in the deployment of the different existing and emerging PV technologies is the understanding of the performance exhibited by each technology, once installed outdoors. In particular, such information is necessary because the outdoor PV electrical characteristics are different from the reference STC characteristics described in manufacturer data-sheets. In this section an overview of the main outdoor performance evaluation parameters is presented and the effects of different environmental and operational factors such as solar irradiance, temperature, spectrum and degradation on PV operation and behavior are described.

3.1 Outdoor evaluated performance parameters

In general, PV manufacturers provide information about the electrical characteristics of modules at STC. Specifically, such information includes the open circuit voltage, V_{OC}, short circuit current, I_{SC}, MPP voltage, V_{MPP}, current I_{MPP}, power, P_{MPP}, efficiency, η, and temperature coefficients. As STC conditions rarely occur outdoors, these parameters are not sufficient to predict PV operation under outdoor conditions and hence the need for independent outdoor assessment of different technologies is pressing.

The main outdoor evaluated PV performance parameters include the energy yield, the outdoor efficiency and performance ratio (PR). More specifically, for grid-connected PV systems the most important parameter is the energy yield, which is closely associated with cost evaluations. In particular, the payback of a PV system and the level of investment are associated with the energy production and the feed-in-tariff scheme in place. The normalized PV system energy yield, Y_f (kWh/kW$_p$), is defined as the total energy produced by a PV system during a period with the dc energy yield, E_{dc} (kWh), further normalized to the nameplate manufacturer dc power, P_0 (kW$_p$), to allow for comparison between the different installed PV technologies (Marion et.al, 2005). The final yield, Y_f, is given by:

$$Y_f = \frac{E_{dc}}{P_0} \tag{1}$$

Furthermore, important performance aspects are obtained by the evaluation of the outdoor efficiency, η (%), and PR (%), for each of the PV technologies installed. The efficiency is given by:

$$\eta = \frac{E_{dc}}{H \times A} \tag{2}$$

where H (kWh/m^2) is the total plane of array irradiation and A (m^2) is the area of the PV array. From the above parameters the PR is calculated and used as a useful way of quantifying the overall effect of losses due to PV module temperature, spectrum, module mismatch and other losses such as optical reflection, soiling and downtime failures. The dc PR, PR_{dc}, is defined as the ratio between the real dc energy production, E_{real} (kWh), and the dc energy the PV array would produce, if it had no losses at STC, E_{STC} (kWh), (Zinsser et al., 2007) and is given by:

$$PR_{dc} = \frac{E_{real}}{E_{STC}} = \frac{E_{dc}}{H \times A \times \eta_{STC}} \tag{3}$$

where η_{STC} (%) is the PV module efficiency at STC.

3.2 Environmental and operational performance effects

In the following section, a survey of previous studies on the environmental and operational effects on the performance of the above-mentioned PV technologies is given. In particular, the investigation summarizes the main findings of the effects of solar irradiance, ambient temperature and spectrum on the performance of c-Si and thin-film technologies. In addition, findings relating to the degradation of each technology are also listed.

3.2.1 Solar irradiance effects

The most important environmental parameter influencing the operation of PV technologies is the irradiance. The operating voltage of a PV device has a logarithmic dependence on irradiance while the current is linearly dependent. Many previous studies have shown that at low irradiance levels there is a decrease in efficiency and performance that also depends on the technology (Biicher, 1997; Paretta et al., 1998; Schumann, 2009; Suzuki et al., 2002; Zinsser et al., 2009).

In this section the effect of solar irradiance on the performance of PV technologies is presented along with a discussion of previously conducted indoor and outdoor investigations. The main difficulties in the assessment of solar irradiance effects arise from the fact that the irradiance is associated with other factors that also affect the performance of PV. These factors include clear sky or diffuse irradiance due to cloudy conditions, low irradiance due to early morning or late afternoon (high AM), spectral and angle of incidence (AOI) effects. In general, the effect of solar irradiance levels on PV performance has been investigated by employing indoor controlled methods. These offer the advantage that other effects such as AOI, spectrum and temperature can be controlled and excluded from the investigation. A common approach used is the acquisition of the current-voltage (I-V) curves at the cell or module level using solar flash simulators, which allow the evaluation and comparison of the efficiency at different specified irradiance levels indoors (Bunea et al., 2006; Reich et al., 2009).

Similarly, the effects of solar irradiance have been investigated in outdoor evaluations by first acquiring I-V curves at again cell or module level and secondly correcting the acquired data-sets to STC temperature, by using measured or manufacturer temperature coefficients (Merten & Andreu, 1998; Paretta et al., 1998). To minimize AOI effects, the PV devices are usually mounted on trackers while to minimize spectral effects, the investigations are usually carried out under clear sky conditions. From the acquired and corrected I-V curves the efficiency at different irradiance levels can also be evaluated and compared.

For some commercial PV technologies, the output power follows closely the irradiation level while for many commercial modules the efficiency was found to decrease by 55 – 90 % from its STC value, at irradiance levels below 200 W/m^2 (Biicher, 1997). The behavior of PV technologies at different irradiance levels has been associated with the series and shunt resistance as at high solar irradiance, high series resistance reduces the fill factor (FF) while at low solar irradiance, FF reduction occurs due to low shunt resistance (Randall & Jacot, 2003). Other investigations have further demonstrated that series resistance losses are mainly responsible for the reduction in the FF for intensities of 60 % of one sun or greater (del Cueto, 1998).

Both mono-c-Si and multi-c-Si technologies exhibit almost constant efficiencies in the irradiance range of 100 - 1000 W/m^2 with mono-c-Si found to outperform multi-c-Si in an investigation performed on commercial PV cells (Reich et al., 2009). In addition, some c-Si cells were found to have higher efficiencies at irradiance intensities in the range 100 - 1000 W/m^2 than at STC and this is attributed to series resistance effects, as a lower current leads to quadratically lower series resistance loss (Reich et al., 2009). For c-Si technologies the efficiency decreases logarithmically in the lower irradiance range of 1 - 100 W/m^2 as the

open circuit voltage, V_{OC}, depends logarithmically on the short circuit current I_{SC}. Subsequently, previous work describing the low light performance based on the evaluated FF has shown that for c-Si and CIS, the FF remains approximately constant for irradiance levels above 200 W/m² while at lower irradiance levels the FF decreases (Mohring & Stellbogen, 2008). Furthermore, CdTe thin-film technology has been reported as having a relatively good low irradiance performance (Heesen et al., 2010;) and specifically to exhibit significant performance increase at medium irradiance levels due to the relatively high series resistance of CdTe devices (Mohring & Stellbogen, 2008). On the other hand, a-Si technology shows a constant FF over the entire range and even below 200 W/m² and this further implies a superior performance for sites with high diffuse light conditions (Mohring & Stellbogen, 2008). For the side-by-side irradiance dependence comparison performed for different commercial PV technologies in Nicosia, Cyprus, the a-Si and CdTe technologies have exhibited higher relative efficiencies at low light (Zinsser et al., 2009).
Because of the importance of this effect it would be very useful if all manufacturers provided, as part of their data-sheet information, the efficiencies at different irradiance levels.

3.2.2 Thermal effects

PV technologies that operate in warm climates experience module temperatures significantly above 25 °C and this is a very important performance loss factor. The parameters which describe the behavior of the electrical characteristics of PV with the operating temperature and hence the thermal effects, are the temperature coefficients (King et al., 1997; Makrides et al., 2009). Another important thermal parameter that describes the temperature of a PV module is the nominal operating cell temperature (NOCT), which is provided by PV manufacturers as an indication of how module temperature is affected by the solar irradiation, ambient temperature and thermal properties of the PV material.
Temperature coefficients of PV devices are usually evaluated using indoor laboratory techniques. A commonly used methodology is to illuminate a PV cell or module that is placed on a temperature controlled structure. Accordingly, the I-V curves of the device are acquired over a range of different cell temperatures but at controlled STC irradiance and AM. The rate of change of either the voltage, current or power with temperature is then calculated and provides the value of the temperature coefficients (King et al., 1997).
In addition, a useful technique to obtain the temperature coefficients under real operating conditions is to employ outdoor field test measurements. In outdoor investigations the PV devices are first shaded to lower the temperature close to ambient conditions and as soon as the device is uncovered and left to increase in temperature, several I-V curves are acquired at different temperatures (Akhmad et al., 1997; King et al, 1997; Makrides et al., 2009; Sutterlüti et al., 2009). As in indoor investigations, the rate of change of the investigated parameter against temperature provides the temperature coefficient. Both techniques are used by manufacturers and professionals within the field. Previous studies have shown that the power of c-Si PV modules decreases by approximately -0.45 %/K (Virtuani et al. 2010; Makrides et al., 2009). On the other hand, thin-film technologies of CdTe and CIGS show lower power temperature coefficients compared to c-Si technologies and in the case of CdTe modules the measured temperature coefficient is around -0.25 %/K (Dittmann et al., 2010). In addition, a-Si shows the lowest power temperature coefficient of up to approximately -0.20 %/K (Hegedus, 2006) while numerous studies have further shown that high module

operating temperatures improve the performance of stabilized a-Si modules due to thermal annealing (Dimitrova et al., 2010; King et al., 2000; Ransome & Wohlgemuth, 2000). The thermal behavior of a-Si suggests that a unique temperature coefficient as in the case of other PV technologies cannot characterize completely the temperature behavior of this technology (Carlson et al., 2000). In general, the output power and performance of CdTe and a-Si modules is less temperature sensitive than CIS and c-Si technologies. Table 2 summarizes the MPP power, P_{MPP}, temperature coefficients of commercial PV technologies.

Technology	Approximate MPP power temperature coefficient, P_{MPP} (%/K)
Mono-c-Si	-0.40
Multi-c-Si	-0.45
a-Si	-0.20
a-Si/μc-Si	-0.26
CIGS	-0.36
CdTe	-0.25

Table 2. Typical power temperature coefficients for different technologies.

3.2.3 Spectral effects

PV devices are affected by the change and variation of the solar spectrum. In practice, the power produced by a PV cell or module can be calculated by integrating the product of the spectral response and the spectrum, at a given temperature and irradiance level, over the incident light wavelength range (Huld et al., 2009). The effect of spectrum is a technology dependent parameter as some technologies are affected more by spectral variations than others (King et al., 1997).

The spectral response of PV technologies is usually known but as the spectral irradiance at different installation locations is unknown, the spectral losses can be difficult to evaluate (Huld et al., 2009). The spectral content of a location is affected by several factors such as the AM, water vapor, clouds, aerosol particle size distribution, particulate matter and ground reflectance (Myers et al., 2002). In clear-sky conditions the spectrum can be described as a function of air mass and relative humidity (Gueymard et al., 2002). In cloudy weather the spectral effects are more complex and in general the light under these conditions is stronger in the blue region of the spectrum than the standard AM 1.5 spectrum. Conversely, the blue region of the spectrum is attenuated as the sun moves lower in the sky (Huld et al., 2009).

A number of studies have been performed both indoors and outdoors to investigate spectral effects (Gottschalg et al., 2007; Merten & Andreu, 1998; Zanesco & Krenziger, 1993). The spectral response of PV cells and modules can be determined indoors using specialized equipment such as solar simulators and special filters at controlled irradiance and temperature conditions (Cannon et al., 1993; Virtuani et al., 2011). In outdoor investigations the spectral behavior of PV devices is usually found by mounting the PV device on a tracker and acquiring measurements of the short circuit current or I-V curves in conjunction with measurements acquired using a pyranometer and a spectroradiometer (King et al., 1997).

The effect of the spectrum has been further described in different ways. Several authors have presented spectral effects by calculating the fraction of the solar irradiation that is usable by each PV technology (Gottschalg et al., 2003). Others have included the average photon energy (APE) parameter, even though this requires knowledge of the spectrum under varying conditions (Gottschalg et al., 2005; Norton et al., 2011). Empirical models have also been considered to account for the influence of the solar spectrum on the short circuit current (Huld et al., 2009).

Technologies of c-Si and CIGS have a wide spectral response and this allows a large spectral absorption. In the case of c-Si technologies an increase in efficiency at high AM and clear sky conditions has been reported (King et al., 2004; Zdanowicz et al., 2003), while other investigations performed on c-Si modules mounted on a tracker under clear sky conditions showed a slight decrease in performance with increasing AM (Kenny et al., 2006). CdTe and a-Si technologies have a narrower spectral response which ranges approximately between 350 - 800 nm and this leads to lower photon absorption. Modules of a-Si have shown higher energy yield compared to c-Si for diffuse light irradiation and high sun elevation angles (Grunow et al., 2009).

Specifically, in a previous study in Japan, the ratio of spectral solar irradiation available for solar cell utilization to global solar irradiation, was found to vary from 5 % for multi-c-Si cells, to 14 % for a-Si cells, throughout a year (Hirata & Tani, 1995). In addition, the experimental results of a study carried out in the UK, showed that on an annual basis, the usable spectral fraction of solar irradiation for a-Si varied from +6 % to -9 % with respect to the annual average, while for CdTe and CIGS it varied in the range of +4 % to -6 % and ±1.5 % (Gottschalg et al, 2003). Spectral effects on PV performance are therefore important depending on the location, climatic conditions and spectral sensitivity of each technology.

3.2.4 PV degradation

The performance of PV modules varies according to the climatic conditions and gradually deteriorates through the years (Adelstein & Sekulic, 2005; Cereghetti et al., 2003; Dunlop, 2005; Osterwald et al., 2006; Sanchez-Friera et al., 2011; Som & Al-Alawi, 1992). An important factor in the performance of PV technologies has always been their long-term reliability especially for the new emerging technologies. The most important issue in long-term performance assessments is degradation which is the outcome of a power or performance loss progression dependent on a number of factors such as degradation at the cell, module or even system level. In almost all cases the main environmental factors related to known degradation mechanisms include temperature, humidity, water ingress and ultra-violet (UV) intensity. All these factors impose significant stress, over the lifetime of a PV device and as a result detailed understanding of the relation between external factors, stability issues and module degradation is necessary. In general, degradation mechanisms describe the effects from both physical mechanisms and chemical reactions and can occur at both PV cell, module and system level.

More specifically, the degradation mechanisms at the cell level include gradual performance loss due to ageing of the material and loss of adhesion of the contacts or corrosion, which is usually the result of water vapor ingress. Other degradation mechanisms include metal mitigation through the p-n junction and antireflection coating deterioration. All the above-mentioned degradation mechanisms have been obtained from previous experience on c-Si technologies (Dunlop, 2005; Quintana et al., 2002; Som & Al-Alawi, 1992).

In the case of a-Si cells an important degradation mechanism occurs when this technology is first exposed to sunlight as the power stabilizes at a level that is approximately 70 - 80 % of the initial power. This degradation mechanism is known as the Staebler-Wronski effect (Staebler & Wronski, 1977) and is attributed to recombination-induced breaking of weak Si-Si bonds by optically excited carriers after thermalization, producing defects that decrease carrier lifetime (Stutzmann et al., 1985).

Other degradation mechanisms have also been observed for thin-film technologies of CdTe and CIGS at the cell level. For CdTe technologies the effects of cell degradation can vary with the properties of the cell and also with the applied stress factors. More specifically, in CdTe technologies as the p-type CdTe cannot be ohmically contacted with a metal, most devices use copper to dope the CdTe surface before contacting (Chin et al., 2010; Dobson et al., 2000). Copper inclusion may cause dramatic changes in the electrical properties of the CdTe thin-film (Chin et al., 2010). As copper is very mobile it can diffuse along grain boundaries of the CdTe cell and result in a recombination center situated close to the p-n junction. Very low levels of copper reduce the conductivity of CdTe and it is possible that the diffusion of copper can transform the back contact to non-ohmic. Another effect associated with CdTe degradation is due to the applied voltage either arising from the cell or the external voltage, which as a result of the electric field it can force copper ions towards the front contact. It was previously found that open-circuit conditions affected cell degradation during accelerated ageing for different CdTe cell types (Powell et al., 1996). In addition, impurity diffusion and changes in doping profiles may affect device stability (Batzner et al., 2004; Degrave et al., 2001), but the industry has resolved this problem by using special alloys.

CIGS has a flexible structure that enhances its tolerance to chemical changes and because of this it has been previously argued that copper atoms do not pose stability problems for CIGS cells (Guillemoles et al., 2000). Damp heat tests performed on unencapsulated CIGS cells have indicated that humidity degrades cell performance and is more obvious as V_{OC} and FF degradation due to the increased concentration of deep acceptor states in the CIGS absorber (Schmidt et al., 2000). Other important factors include donor-type defects (Igalson et al., 2002) and the influence of Ga-content on cell stability (Malmström et al., 2003).

At the module level, degradation occurs due to failure mechanisms of the cell and in addition, due to degradation of the packaging materials, interconnects, cell cracking, manufacturing defects, bypass diode failures, encapsulant failures and delamination (King et al., 1997; Pern at al., 1991; Wenham et al., 2007).

At the system level, degradation includes all cell and module degradation mechanisms and is further caused by module interconnects and inverter degradation. Table 3 summarizes the main thin-film failure modes and failure mechanisms (McMahon, 2004).

Indoor degradation investigations are mainly performed at the module level as the interconnection and addition of other materials to form a modular structure increases stability issues. In particular, accelerated ageing tests performed indoors and under controlled conditions can provide information about different degradation mechanisms. Degradation investigations using indoor methodologies are based on the acquisition of I-V curves and power at STC. The electrical characteristics of PV modules are initially measured at STC and then the modules are either exposed outdoors or indoors through accelerated procedures (Carr & Pryor, 2004; Meyer & van Dyk, 2004; Osterwald et al., 2002). For each investigated PV cell or module the electrical characteristics are regularly acquired using the solar simulator and the current, voltage or power differences from the initial value provide indications of the degradation rates at successive time periods.

In addition, many groups have performed outdoor monitoring of individual PV modules through the acquisition and comparison of I–V curves, as the modules are exposed to real outdoor conditions (Akhmad et al., 1997; Ikisawa et al., 1998; King et al., 2000). Another method to investigate degradation outdoors has been based on power and energy yield measurements of PV systems subjected to actual operating conditions. A common approach has been to first establish time series usually on a monthly basis, of either the PR or the maximum power normalised to Photovoltaics for Utility Scale Applications (PVUSA) Test Conditions (PTC) of solar irradiance 1000 W/m², air temperature of 20 °C and wind speed of 1 m/s. Time series analysis such as linear regression, classical series decomposition (CSD) and Autoregressive Integrated Moving Average (ARIMA) is then used to obtain the trend and hence the degradation rate (Jordan & Kurtz, 2010; Osterwald et al., 2002). Outdoor field tests are very important in exploring the degradation mechanisms under real conditions. These mechanisms cannot otherwise be revealed from indoor stability tests. The outcome of such outdoor investigations can provide useful feedback to improve the stability, enhance the understanding of the different technology dependent degradation mechanisms and can be used as tools for the adaptation of accelerated ageing tests so as to suit the degradation mechanisms for each technology.

Failure modes	Effect on I-V curve	Possible failure mechanisms
1. Cell degradation		
a. Main junction: increased recombination	Loss in fill factor, *I*sc, and *V*oc	Diffusion of dopants, impurities, etc. Electromigration
b. Back barrier; loss of ohmic contact (CdTe)	Roll-over, cross-over of dark and light I–V, higher R_{series}	Diffusion of dopants, impurities, etc. Corrosion, oxidation Electromigration
c. Shunting	R_{shunt} decreases	Diffusion of metals, impurities, etc.
d. Series; ZnO,Al	R_{series} increases	Corrosion, diffusion
e. De-adhesion SnO_2 from soda-lime glass	Isc decreases and R_{series} increases	Na ion migration to SnO_2/glass interface
f. De-adhesion of back metal contact	Isc decreases	Lamination stresses
2. Module degradation		
Interconnect degradation		
a. Interconnect resistance; ZnO:Al/Mo or Mo, Al interconnect	R_{series} increases	Corrosion, electromigration
b. Shunting; Mo across isolation scribe	R_{shunt} decreases	Corrosion, electromigration
Busbar degradation	R_{series} increases or open circuit	Corrosion, electromigration
Solder joint	R_{series} increases or open circuit	Fatigue, coarsening (alloy segragation)
Encapsulation failure		
a. Delamination	Loss in fill-factor, *I*sc, and possible open circuit	Surface contamination, UV degradation, hydrolysis of silane/glass bond, warped glass, 'dinged' glass edges, thermal expansion mismatch
b. Loss of hermetic seal		
c. Glass breakage		
d. Loss of high-potential isolation		

Table 3. Thin-film failure modes and failure mechanisms (McMahon, 2004).

For both indoor and outdoor evaluations a variety of degradation rates have been reported and a survey of the results of degradation studies is given below. A recent study has shown that on average the historically reported degradation rates of different PV technologies was 0.7 %/year while the reported median was 0.5 %/year (Jordan et al., 2010). More specifically, investigations performed on outdoor exposed mono and multi-c-Si PV modules showed performance losses of approximately 0.7 %/year (Osterwald et al., 2002). Results of field tests have generally shown stable performance for CdTe devices (del Cueto, 1998; Mrig & Rummel, 1990; Ullal et al., 1997), although field results are limited for modules utilizing new cell structures (Carlsson & Brinkman, 2006). Previous studies performed on thin-film CIS modules, showed that after outdoor exposure the efficiency was found to decrease (Lam et al., 2004) and to exhibit either moderate, in the range of 2 - 4 %/year, to negligible or less than 1 %/year degradation rates due to increases in the series resistance in some of the modules (del Cueto et al., 2008).

Evaluations based on monthly PR and PVUSA values revealed degradation rates, for the PR investigation, of 1.5 %/year for a-Si, 1.2 %/year for CdTe and 0.9 %/year for mono-c-Si (Marion et al., 2005). The results were slightly different for the PVUSA investigation which showed a degradation rate of 1.1 %/year for the a-Si, 1.4%/year for the CdTe and 1.3 %/year for the mono-c-Si (Marion et al., 2005). Based on linear fits applied to the PVUSA power rating curves over the six year time period for a thin-film a-Si system, degradation rates of 0.98 %/year at the dc side and 1.09 %/year at the ac side of the system were obtained while the same investigation on PR data-sets indicated a similar degradation rate of 1.13 %/year at the ac side (Adelstein & Sekulic, 2005). Additionally, in a recent long-term performance assessment of a-Si tandem cell technologies in Germany it was demonstrated that an initial two year stabilization phase occurred and was then followed by a stable phase with a minor power decrease of maximum 0.2 %/year (Lechner et al., 2010). In a different study it was reported that thin-film modules showed somewhat higher than 1 %/year degradation rates (Osterwald et al., 2006). On the other hand, an important consideration in relation to thin-film degradation rate investigations was found to be the date of installation of the modules as it appeared that in the case of CdTe and CIGS modules manufactured after 2000 exhibited improved stability relative to older designs (Jordan et al., 2010).

4. Performance assessment of different PV technologies under outdoor conditions

In the previous section a general description of the main outdoor evaluation performance parameters and the effects of different environmental and operational parameters was given. In the following section, a discussion on the work carried out at the outdoor test facility in Cyprus, related to the performance assessment of different installed PV technologies is presented. An infrastructure was set up for continuous and simultaneous monitoring of a number of PV systems (together with weather and irradiation data) and to thereby assess their performance under the exact same field conditions. The knowledge acquired from the field testing, described in this section, is important to enhance the understanding of the underlying loss processes and to optimise the systems performance. Furthermore, it is essential to continue testing as the current PV technologies become more mature and new technologies are entering the market. The same infrastructure installed in Cyprus was also replicated in two other locations for the scope of investigating the performance of different PV technologies under different climatic conditions. The three selected locations include the Institut für Physikalische Elektronik (*ipe*) University of Stuttgart, Germany, the University of Cyprus (UCY), Nicosia, Cyprus and the German University in Cairo (GUC) Cairo, Egypt.

4.1 PV test facility description

The outdoor test facility at the University of Cyprus, Nicosia, Cyprus was commissioned in May 2006 and includes, amongst others, 12 grid-connected PV systems of different technologies. The fixed-plane PV systems installed range from mono-c-Si and multi-c-Si, Heterojunction with Intrinsic Thin layer (HIT), Edge defined Film-fed Growth (EFG), Multi-crystalline Advanced Industrial cells (MAIN) to a-Si, CdTe, CIGS and other PV technologies. Table 4 provides a brief description of the installed systems (Makrides et al., 2010).

Manufacturer	Module type	Technology	Rated module efficiency (%)
Atersa	A-170M 24V	Mono-c-Si	12.9
BP Solar	BP7185S	Mono-c-Si (Saturn-cell)	14.8
Sanyo	HIP-205NHE1	Mono-c-Si (HIT-cell)	16.4
Suntechnics	STM 200 FW	Mono-c-Si (back contact-cell)	16.1
Schott Solar	ASE-165-GT-FT/MC	Multi-c-Si (MAIN-cell)	13.0
Schott Solar	ASE-260-DG-FT	Multi-c-Si (EFG)	11.7
SolarWorld	SW165 poly	Multi-c-Si	12.7
Solon	P220/6+	Multi-c-Si	13.4
Mitsubishi Heavy Industries (MHI)	MA100T2	a-Si (single cell)	6.4
Schott Solar	ASIOPAK-30-SG	a-Si (tandem cell)	5.4
First Solar	FS60	CdTe	8.3
Würth	WS 11007/75	CIGS	10.3

Table 4. Installed PV types of modules.

The monitoring of the PV systems started at the beginning of June 2006 and both meteorological and PV system measurements are being acquired and stored through an advanced measurement platform. The platform comprises meteorological and electrical sensors connected to a central data logging system that stores data at a resolution of one measurement per second. The monitored meteorological parameters include the total irradiance in the POA, wind direction and speed as well as ambient and module temperature. The electrical parameters measured include dc current and voltage, dc and ac power at MPP as obtained at each PV system output (Makrides et al., 2009).

4.2 PV performance evaluation

The weather conditions recorded over the evaluation period in Cyprus showed that there is a high solar resource and exposure to warm conditions. The annual solar irradiation, over the period June 2006 - June 2010 is summarised in Table 5.

Period	Solar Irradiation (kWh/m²)
June 2006 - June 2007	1988
June 2007 - June 2008	2054
June 2008 - June 2009	1997
June 2009 - June 2010	2006

Table 5. Solar irradiation over the period June 2006 - June 2010 in Nicosia, Cyprus.

A detailed analysis of the prevailing climatic conditions was performed on the acquired 15-minute average measurements, in order to obtain the fraction of solar irradiation in Cyprus, the average ambient air temperature and PV operating temperature at different solar irradiance levels over the four-year evaluation period. Table 6 shows the results of the average ambient and PV module temperature (Atersa mono-c-Si fixed-plane module temperatures presented) at different solar irradiation levels over the first, second, third and fourth year respectively. The results indicate that the PV module operating temperatures increased above the STC temperature of 25 °C at POA solar irradiance over 201 W/m². During the first three years, the highest amount of solar irradiation occurred within the range 801 - 900 W/m² while in the fourth year within the range 901 - 1000 W/m².

Solar Irradiance (W/m”)	Total irradiation fraction (%)				Ambient temperature (°C)				PV module temperature (°C)			
	2006-2007	2007-2008	2008-2009	2009-2010	2006-2007	2007-2008	2008-2009	2009-2010	2006-2007	2007-2008	2008-2009	2009-2010
0 - 100	2.0	1.8	1.9	2.0	15.4	16.2	16.4	16.9	14.7	15.4	15.8	16.3
101 - 200	2.8	2.4	2.6	2.7	20.2	21.0	20.3	20.1	24.1	24.6	24.0	23.9
201 - 300	4.1	4.0	4.3	4.2	21.5	22.3	22.1	22.6	27.3	27.8	27.9	28.5
301 - 400	5.3	5.1	5.8	5.6	22.3	23.3	23.0	23.4	30.7	31.4	31.4	31.8
401 - 500	7.0	7.3	7.4	7.0	22.9	23.6	23.5	23.7	33.5	34.0	34.4	34.6
501 - 600	9.7	10.0	9.5	9.2	23.4	23.7	23.9	24.5	36.8	37.0	37.4	38.1
601 - 700	12.9	13.3	12.0	11.6	24.7	24.6	25.1	25.4	41.3	40.8	41.4	41.6
701 - 800	16.9	18.1	15.7	14.5	25.7	25.5	25.9	25.9	45.2	44.3	44.9	44.8
801 - 900	20.9	21.4	20.0	18.0	26.4	28.2	27.2	27.5	48.1	49.7	48.8	48.6
901 - 1000	15.8	14.3	15.9	21.2	27.2	29.0	29.0	30.2	50.4	51.6	52.0	53.5
1001 - 1100	2.5	2.2	4.4	3.8	23.3	23.6	23.0	26.1	47.3	46.7	46.5	50.2
> 1101	0.0	0.0	0.4	0.1	24.7	24.0	20.1	17.5	47.2	51.9	46.0	40.2

Table 6. Solar irradiation fraction, average ambient and module temperature (Atersa mono-c-Si) at different irradiance levels, over the period June 2006 - June 2010 in Nicosia, Cyprus.

During the first year of operation the fixed-plane PV systems showed an average annual dc energy yield of 1738 kWh/kW$_p$ while during the second year of operation and for the same systems the average dc energy yield was 1769 kWh/kW$_p$, showing an increase of 1.8 % in comparison to the first year. The average dc energy yield was lower during the third and fourth year with 1680 kWh/kW$_p$ and 1658 kWh/kW$_p$ respectively. The annual dc energy yield normalized to the manufacturer's rated power over the period June 2006 - June 2010 in Nicosia, Cyprus is shown in Table 7. It must be noted that partial shading affected the BP Solar mono-c-Si and Solon multi-c-Si systems specifically during the second, third and fourth year while the Schott Solar a-Si system had a broken module since October 2006.

System	Normalized DC Energy Yield (kWh/kW$_p$)			
	2006 - 2007	2007 - 2008	2008 - 2009	2009 - 2010
Atersa (A-170M 24V)	1753	1810	1744	1719
BP Solar (BP7185S)	1612	1593	1457	1510
Sanyo (HIP-205NHE1)	1790	1814	1731	1703
Suntechnics (STM 200 FW)	1864	1890	1800	1793
Schott Solar (ASE-165-GT-FT/MC)	1752	1810	1736	1712
Schott Solar (ASE-260-DG-FT)	1721	1783	1714	1688
SolarWorld (SW165)	1731	1772	1689	1654
Solon (P220/6+)	1715	1761	1681	1637
MHI (MA100T2)	1734	1734	1644	1617
Schott Solar (ASIOPAK-30-SG)	1599	1650	1571	1554
Würth (WS 11007/75)	1827	1863	1748	1707
First Solar (FS60)	1755	1752	1645	1605

Table 7. Annual dc energy yield normalized to the manufacturer's rated power over the period June 2006 - June 2010 in Nicosia, Cyprus.

During the first year of operation the best performing technologies in Nicosia, based on the annual dc energy yield, were the Suntechnics mono-c-Si, the Würth CIGS, the Sanyo HIT mono-c-Si and the First Solar CdTe. During the second year the mono-c-Si technologies of Sanyo, Suntechnics and the CIGS retained their high energy yield. During the third year the highest energy yield was produced by the Suntechinics mono-c-Si, Würth CIGS and Atersa mono-c-Si system. During the fourth year the first three technologies which produced the highest yield were entirely c-Si, the Suntechnics, Atersa mono-c-Si and the Schott Solar (MAIN) multi-c-Si while the Würth CIGS system followed.

The comparison of the annual dc energy yield produced by the same technology modules, Atersa mono-c-Si fixed-plane, installed in the POA of 27.5° and also mounted on a two-axis tracker is shown in figure 1. Over a four-year period, the tracker provided on average 21 % higher energy yield compared to the fixed-plane system. During the first year, the solar irradiation collected by the reference cell installed at the tracker was 2532 kWh/m^2 while during the second year it was 2606 kWh/m^2 (Makrides et al., 2010). Subsequently, during the third and fourth year the solar irradiation collected by the tracker was 2510 kWh/m^2 and 2483 kWh/m^2 respectively.

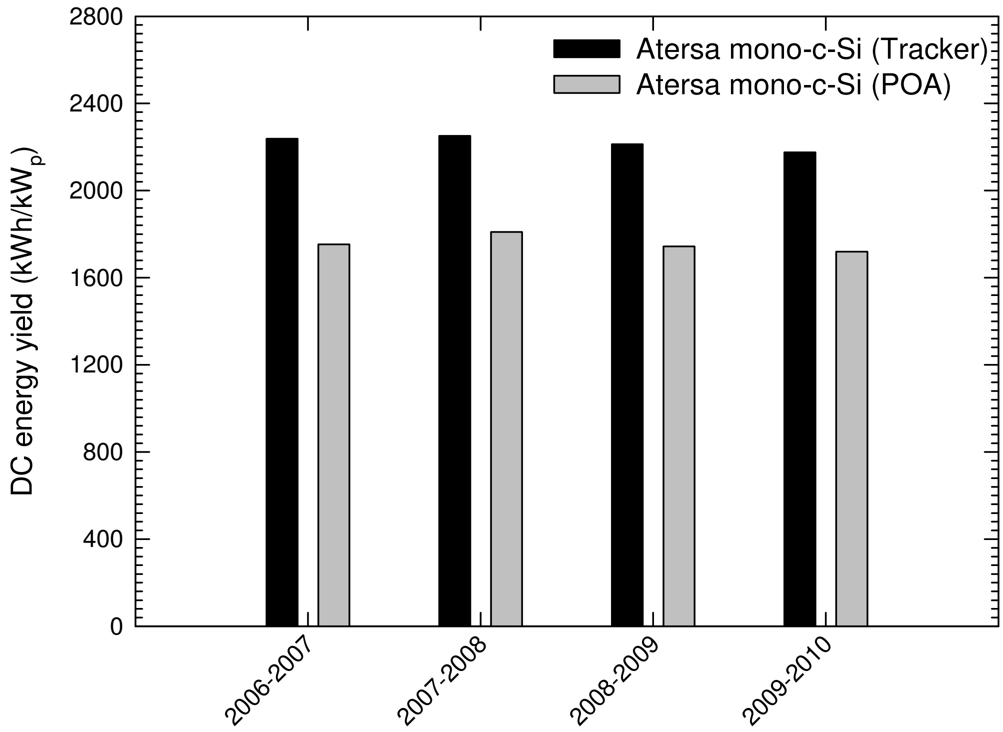

Fig. 1. Comparison of the annual dc energy yield of the tracker and fixed-plane Atersa mono-c-Si systems over the period June 2006 - June 2010.

Table 8 shows the annual ac energy yield normalized to the manufacturer's rated power.

System	Normalized AC Energy Yield (kWh/kW$_p$)			
	2006 - 2007	2007 - 2008	2008 - 2009	2009 - 2010
Atersa (A-170M 24V)	1593	1646	1583	1564
BP Solar (BP7185S)	1463	1445	1320	1370
Sanyo (HIP-205NHE1)	1630	1659	1581	1555
Suntechnics (STM 200 FW)	1692	1717	1641	1638
Schott Solar (ASE-165-GT-FT/MC)	1588	1642	1575	1552
Schott Solar (ASE-260-DG-FT)	1562	1620	1554	1532
SolarWorld (SW165)	1573	1613	1535	1500
Solon (P220/6+)	1567	1609	1533	1495
MHI (MA100T2)	1573	1575	1495	1466
Schott Solar (ASIOPAK-30-SG)	1462	1506	1433	1419
Würth (WS 11007/75)	1653	1691	1581	1543
First Solar (FS60)	1599	1600	1500	1461

Table 8. Annual ac energy yield normalized to the manufacturer's rated power over the period June 2006 - June 2010 in Nicosia, Cyprus.

4.3 Effects of environmental and operational parameters on PV performance

In the following section, a summary of the investigations and outcomes related to the seasonal performance and the effect of temperature, soiling and STC power normalization on the performance assessment of the installed technologies in Cyprus is given.

4.3.1 PV seasonal performance evaluation using outdoor measurement analysis

In order to observe the effects of environmental conditions on the outdoor performance of the installed PV technologies, a seasonal performance investigation was carried out. Specifically, a time series was constructed of the monthly average dc PR over the four-year evaluation period. The plots in figure 2 depict the constructed monthly average dc PR time series of all the PV technologies. It is evident from the plots that all technologies exhibit a seasonal behavior with peaks according to the seasons and with progressive performance loss that is more evident in some technologies than others. Both mono-c-Si and multi-c-Si technologies exhibited PR peaks during the cold winter season and performance decrease during the warm summer months as depicted in figures 2a and 2b respectively. The Suntechnics mono-c-Si exhibited high monthly PR that approached the optimum (PR of 100 %) during the winter seasons and in one case, December 2006, this value was even exceeded. This can occur because of the associated power rating and irradiation uncertainties that are present also in the calculated monthly PR value. From the PR plot of figure 2c of the a-Si technologies it was obvious that during the summer and early autumn, the performance was higher than in the winter. In addition, the high initial monthly PR of the a-Si technologies is primarily attributed to the fact that these technologies had not yet stabilized. Accordingly, the same seasonal performance pattern as the one of c-Si technologies was observed for the Würth CIGS and First Solar CdTe, shown in figure 2d. In the case of the First Solar CdTe system a narrower peak-to-peak PR variation between the seasons was observed compared to the c-Si and CIGS seasonal behavior.

4.3.2 Thermal effects

In countries such as Cyprus with a high solar resource and warm climate the extent to which PV technologies are affected by temperature is an important criterion for their selection. Investigations to evaluate the effect of temperature were performed based on an indoor and outdoor procedure for the extraction of the MPP power temperature coefficients of the installed technologies (Makrides et al., 2009).

For the outdoor procedure, the temperature coefficients at the MPP power were extracted from a series of acquired I-V curve measurements over a range of temperatures (from ambient to maximum module temperature during the period of outdoor measurements). The outdoor investigation was performed during periods of the day with conditions of stable sunshine and calm winds (lower than 2 m/s) around solar noon. All the PV systems were equipped with back surface temperature sensors that were mounted at the centre of each investigated module. At the same time, the MPP power temperature coefficients were also calculated through a filtering and analysis technique (data-evaluated technique) on acquired data over a period of a year. In this investigation 15-minute average data acquired over a period of one year were used. The MPP power data-sets that occurred when the solar irradiance was between 700 and 1100 W/m^2, were chosen in order to minimize the influence of large AM in the morning and the evening. Figure 3 summarizes the measured, calculated and manufacturer provided MPP power temperature coefficients obtained by both techniques. For most PV technologies the outdoor evaluated results showed satisfactory agreement when compared to manufacturer provided data.

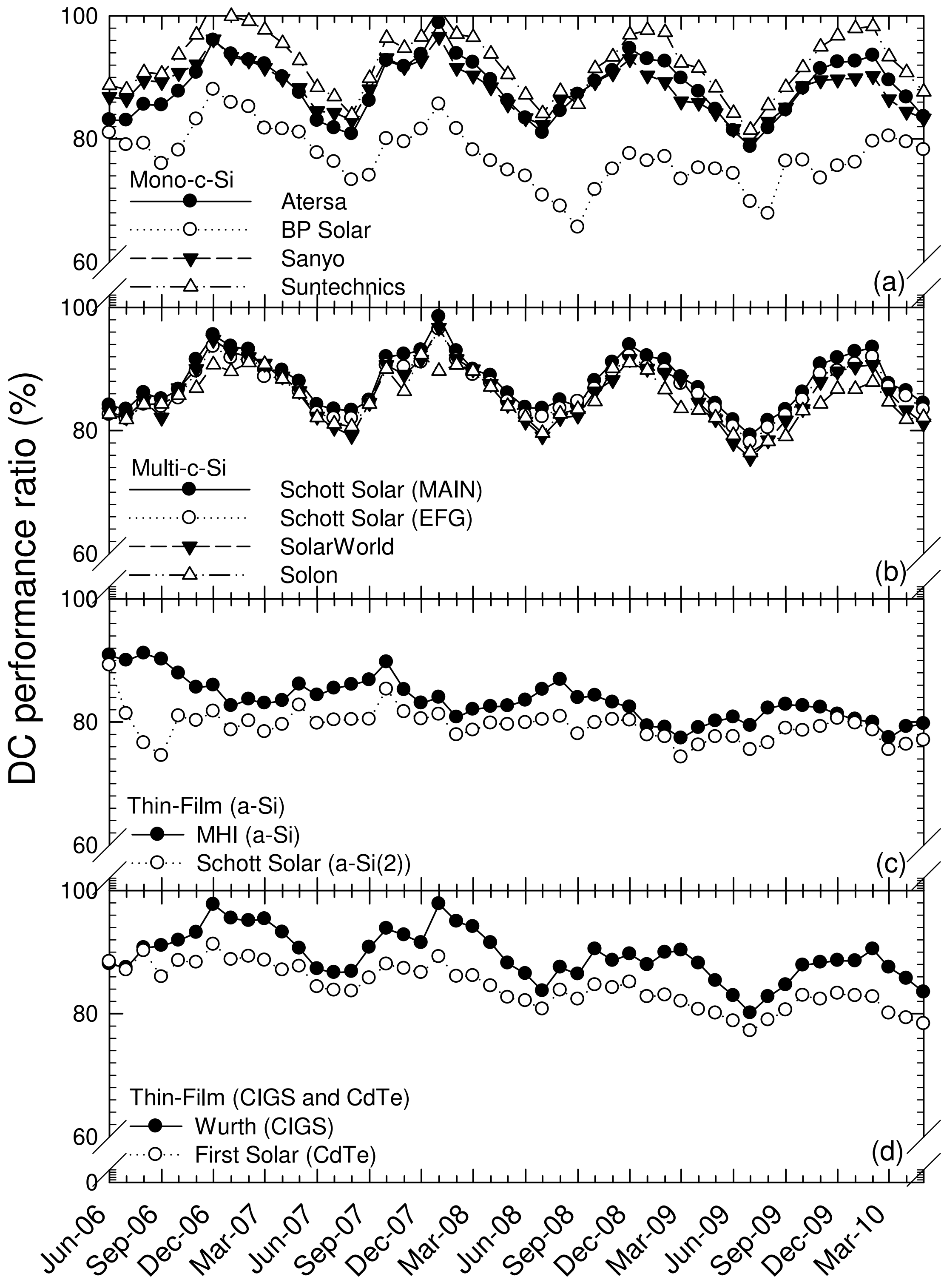

Fig. 2. Monthly average dc PR of installed PV systems over the period June 2006 - June 2010 in Nicosia, Cyprus.

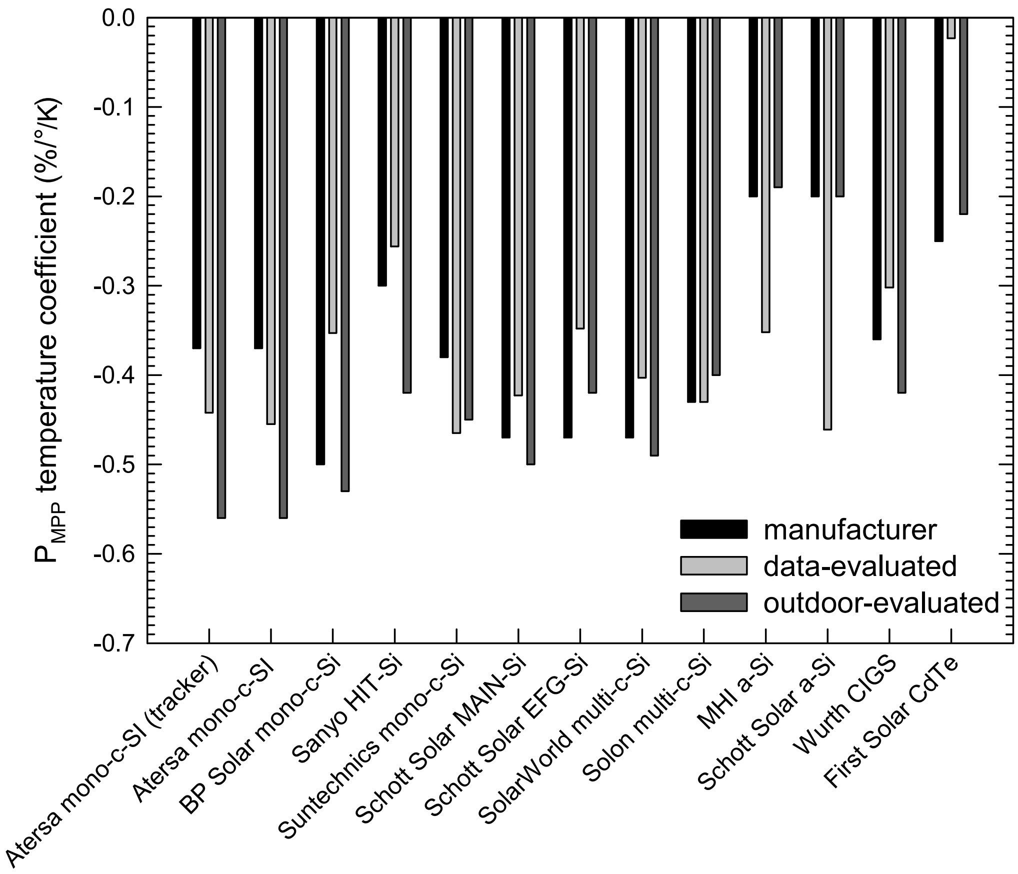

Fig. 3. Comparison of the MPP power temperature coefficients (γ_{PMPP} %/K) obtained by the two methods outlined above (outdoor measurements and data analysis) and the manufacturers' data for the installed systems.

4.3.3 Soiling effects

Soiling describes the accumulation of dirt on the front surface of PV modules and is an important loss factor particularly in locations when there is scarce rain, very dry conditions and even frequent dust or sand storms. The power loss due to soiling is therefore a function of the type of dust, the length of time since the last rainfall and the cleaning schedule (Kymakis et al., 2009). In warm climates such as the one in Cyprus, soiling losses increase as the periods between successive rainfalls increase and this is more noticeable during the summer period.

In general, the standard industry assumption of soiling losses ranges from 1 - 4 % on an annual basis (Detrick et al., 2005). In areas of frequent rainfall, it was demonstrated that the rain could clean the PV modules to an extent of restoring the performance to within 1 % of full power (Hammond et al., 1997). Accordingly, in a more recent soiling analysis performed in Crete, with climatic conditions almost identical to Cyprus, the annual soiling loss was 5.86 %, with the winter losses being 4 - 5 % and 6 - 7 % in the summer (Kymakis et al., 2009).

A soiling investigation was carried out also for the systems installed in Egypt and specifically by comparing the energy produced by a clean module, a module that has been exposed to dust for a period of one year and a module that has been exposed to dust but cleaned every two months. The energy production results showed that the 'one year dusty module' produced 35 % lower energy while the 'two month dusty module' produced 25 % lower energy compared to the clean module (Ibrahim et al., 2009). Figure 4 shows the soiling accumulation after a period of one year for the systems installed in Egypt.

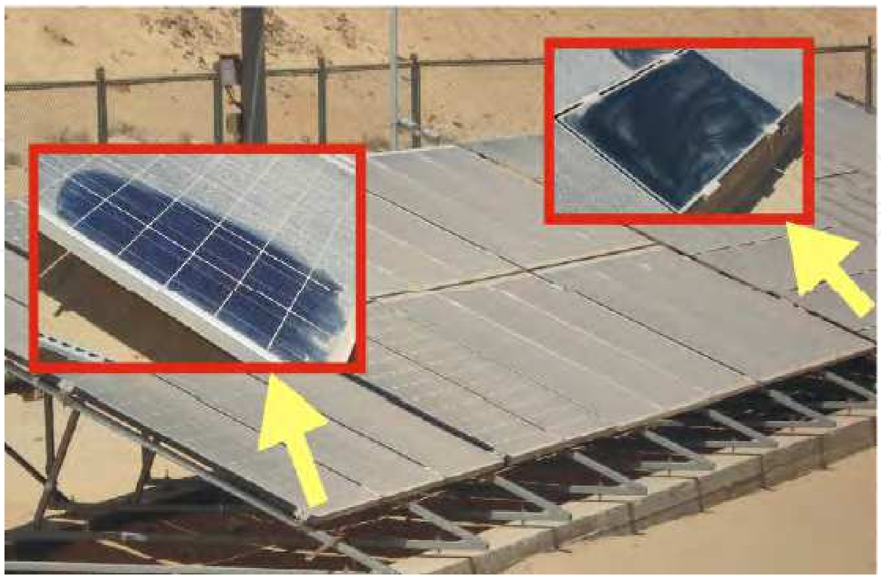

Fig. 4. Dust layer accumulation on PV modules in Egypt (Ibrahim et al., 2009).

4.3.4 Energy yield normalization to rated power and uncertainties

The tolerance of the rated power provided by manufacturers is another important factor that affects the PV performance investigation as it increases the uncertainty of the results. In general, the rated power value is associated with a typical tolerance of ±3 % for c-Si PV modules, and ±5 % for thin-film modules. This uncertainty arises due to the power mismatch of PV cells during module production and the sorting which is necessary so as to avoid power mismatch at array wiring. Subsequently, manufacturers measure the power of each produced module using a flasher and then sort the modules into power classes (Zinsser et al., 2010). The uncertainty associated with the power rating is particularly important in outdoor PV performance evaluations and comparisons as in the case of the normalized annual energy yield (kWh/kW_P) to the rated power (Zinsser et al., 2010).

By considering an uncertainty of ±3 % due to the STC power and a ±2 % due to the ac energy measurement and acquisition, a difference of up to 10 % could arise for comparisons between the annual yields of two PV systems at the same location. The high power rating uncertainty value is a limiting factor in performance investigations as it is very difficult to distinguish which of those systems performed better over a period of time. Figure 5 shows the annual ac energy yield and associated power rating and measurement uncertainties over the four-year period and the average energy yield of the flat plate systems.

The uncertainty makes it difficult to accurately distinguish which technology had produced the highest energy. In addition, this uncertainty is also large enough to mask other lower-order performance effects, such as degradation rate, spectral losses and other performance loss factors. In the absence of the power rating uncertainty these effects would have been important in the energy yield comparisons and the selection of the best performing technology at a particular location. Therefore, there is a high need for low uncertainties in the power tolerance of PV modules.

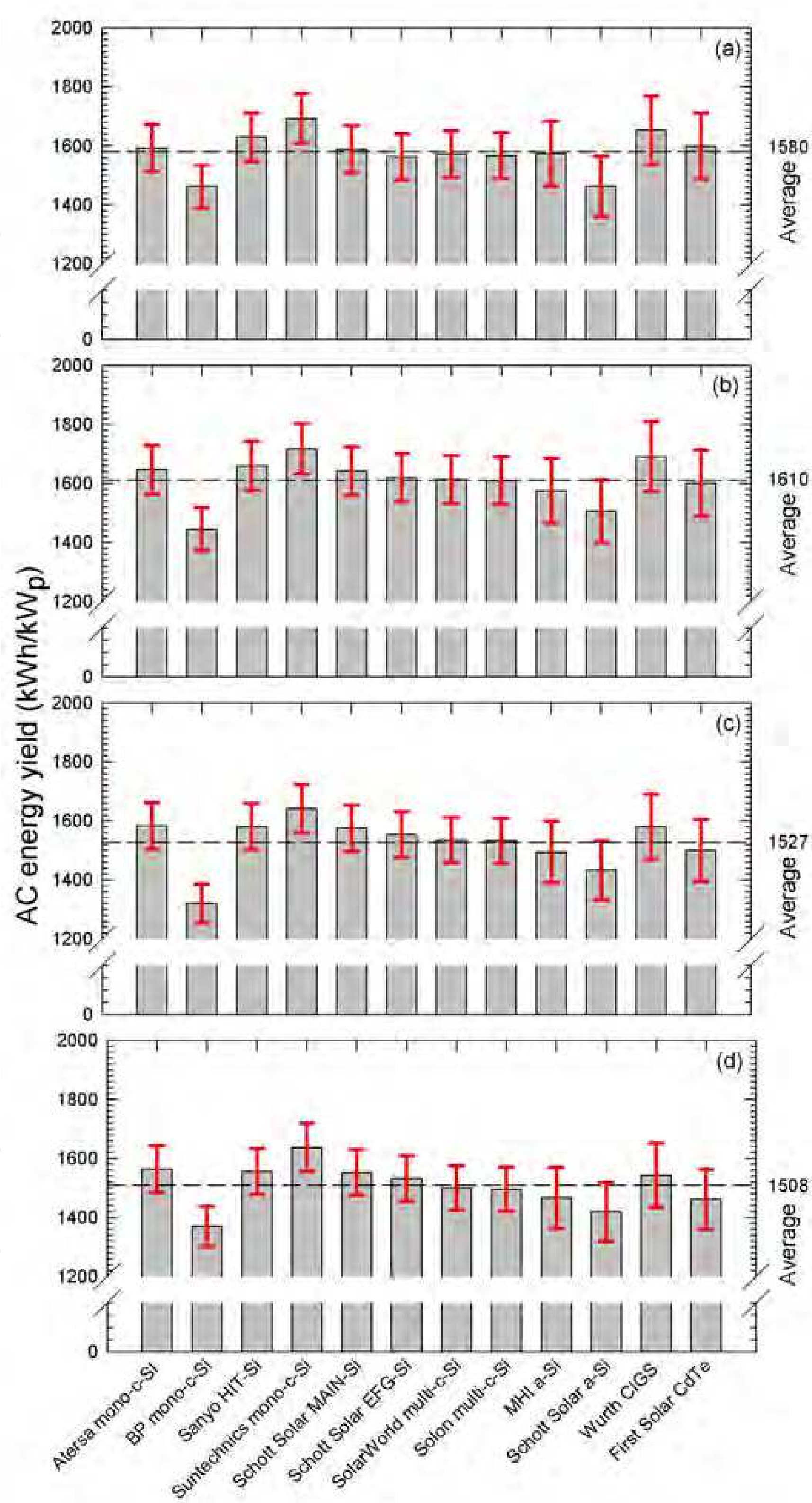

Fig. 5. Annual ac energy yield normalized to rated power over the period a) June 2006 - June 2007, b) June 2007 - June 2008, c) June 2008 - June 2009 and d) June 2009 - June 2010. The error bars represent the associated power rating and measurement uncertainty.

5. Conclusion

The emergence and continuous increase in deployment of different PV technologies such as c-Si, thin-film and CPV, provide evidence that PV can become a leading energy source in the future. The success of each technology depends mainly on the capability of meeting targets such as the enhancement of manufacturing procedures while at the same time, accomplishing efficiency increases and cost reductions.

With the vast variety of PV technologies present in the market, it is important to acquire information about their outdoor performance. The main PV performance parameters include the energy yield, the efficiency and PR. These parameters provide the basis of all performance assessments and loss factor investigations. The main environmental factors affecting PV performance include solar irradiance, ambient temperature and solar spectrum. Another important factor for consideration is degradation. Good understanding of the outdoor performance of different PV technologies is a key requirement for their successful integration under different climatic conditions.

In addition to the review of several factors affecting PV performance, the main results of the outdoor investigation carried out in Cyprus over a four-year period have been presented. In particular, useful information on the performance of different PV technologies installed side-by-side was obtained by investigating their seasonal performance and the effects of temperature, soiling and power rating. The outcome of the outdoor performance assessment also showed that these technologies have enormous potential in countries with high solar resource.

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7. References

Adelstein, J. & Sekulic, B. (2005). Performance and Reliability of a 1-kW Amorphous Silicon Photovoltaic Roofing System, *Proceedings of the 31st IEEE Photovoltaics Specialists Conference*, pp. 1627-1630, ISBN 0-7803-8707-4, Lake Buena Vista, USA, January 2005

Akhmad, K.; Kitamura, A.; Yamamoto, F.; Okamoto, H.; Takakura H. & Hamakawa, Y. (1997). Outdoor Performance of Amorphous Silicon and Polycrystalline Silicon PV Modules. *Solar Energy Materials and Solar Cells*, Vol.46, No.3, (June 1997), pp. 209-218

Batzner D.; Romeo, A.; Terheggen, M.; Dobeli, M.; Zogg, H. & Tiwari, A.N. (2004). Stability Aspects in CdTe/CdS Solar Cells. *Thin Solid Films*, Vol.451-452, March 2004, pp. 536-543

Biicher, K. (1997). Site Dependence of the Energy Collection of PV Modules. *Solar Energy Materials and Solar Cells*, Vol.47, No.1-4, (October 1997), pp. 85-94

Britt, J. & Ferekides, C. (1993). Thin-Film CdS/CdTe Solar Cell With 15.8% Efficiency. *Applied Physics Letter*, Vol.62, No.22, (May 1993), pp. 2851-2852, ISSN 0003-6951

Bunea, G.E.; Wilson, K.E.; Meydbray, Y.; Campbell, M.P. & De Ceuster, D.M. (2006). Low Light Performance of Mono-Crystalline Silicon Solar Cells, *Proceedings of the 4th IEEE World Conference on Photovoltaic Energy Conversion*, pp. 1314-1314, ISBN 1-4244-0017-1, Waikoloa, USA, May 2006

Cannon, T.W.; Hulstrom, R. & Trudell, D.T. (1993). New Instrumentation for Measuring Spectral Effects During Outdoor and Indoor PV Device Testing, *Proceedings of the 23rd IEEE Photovoltaic Specialists Conference*, pp. 1176-1179, ISBN 0-7803-1220-1, Lousiville, USA, May 1993

Carlson, D.E.; Lin, G. & Ganguly, G. (2000). Temperature Dependence of Amorphous Silicon Solar Cell PV Parameters, *Proceedings of the 28th IEEE Photovoltaic Specialists Conference*, pp. 707- 712, ISBN 0-7803-5772-8, Anchorage, USA, September 2000

Carlsson, T. & Brinkman, A. (2006). Identification of Degradation Mechanisms in Field-tested CdTe Modules. *Progress in Photovoltaics: Research and Applications*, Vol.14, No.3, May 2006, pp. 213–224

Carr, A.J. & Pryor, T.L (2004). A Comparison of the Performance of Different PV Module Types in Temperate Climates. *Solar Energy*, Vol.76, No.1-3, January-March 2004, pp. 285–294

Cereghetti, N.; Bura, E.; Chianese, D.; Friesen, G.; Realini, A. & Rezzonico, S. (2003). Power and Energy Production of PV Modules Statistical Considerations of 10 Years Activity, *Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion*, pp. 1919-1922, ISBN 4-9901816-0-3, Osaka, Japan, May 2003

Chin, K. K.; Gessert, T.A. & Su-Huai, W. (2010). The Roles of Cu Impurity States in CdTe Thin Film Solar Cells, *Proceedings of the 35th IEEE Photovoltaics Specialists Conference*, pp. 1915-1918, ISBN 978-1-4244-5890-5, Honolulu, USA, June 2010

Cousins, P.J.; Smith, D.D.; Hsin-Chiao, L.; Manning, J.; Dennis, T.D.; Waldhauer, A.; Wilson, K.E.; Harley, G. & Mulligan, W.P. (2010). Generation 3: Improved Performance at Lower Cost, *Proceedings of 35th IEEE Photovoltaics Specialists Conference*, pp. 278-278, ISBN 978-1-4244-5890-5, Honolulu, Hawaii, USA, June 2010

Cusano, D.A. (1963). CdTe Solar Cells and Photovoltaic Heterojunctions in II–VI Compounds. *Solid-State Electron*, Vol.6, No.3, (May-June 1963), pp. 217-218

Degrave S.; Nollet P.; Stojanoska G.; Burgelman M. & Durose K. (2001). Interpretation of Ageing Experiments on CdTe/CdS Solar Cells. *Proceedings of 17th International Photovoltaic Science and Engineering Conference*, pp. 1058-1061, Fukuoka, December 2007 del Cueto, J.A. (1998). Method for Analyzing Series Resistance and Diode Quality Factors From Field Data of Photovoltaic Modules. *Solar Energy Materials and Solar Cells*, Vol.55, No.3, (August 1998), pp. 291-297

del Cueto, J.A; Rummel, S.; Kroposki, B.; Osterwald, C. & Anderberg, A. (2008). Stability of CIS/CIGS Modules at the Outdoor Test Facility Over Two Decades, *Proceedings of the 33rd IEEE Photovoltaic Specialists Conference*, pp. 1-6, ISBN 978-1-4244-1640-0, San Diego, USA, May 2008

Detrick, A.; Kimber, A. & Mitchell, L. (2005). Performance Evaluation Standards for Photovoltaic Modules and Systems, *Proceedings of the 31st IEEE Photovoltaics Specialists Conference*, pp. 1581-1586, ISBN 0-7803-8707-4, Lake Buena Vista, USA, January 2005

Dimitrova, M.; Kenny, R.P.; Dunlop, E.D. & Pravettoni, M. (2010). Seasonal Variations on Energy Yield of A-Si, Hybrid and Crystalline Si PV Modules. *Progress in Photovoltaics: Research and Applications*, Vol.18, No.5, (May 2010), pp. 311-320

Dittmann, S.; Durisch, W.; Mayor, J.C.; Friesen, G. & Chianese, D. (2010). Comparison of Indoor and Outdoor Characterisation of a CdTe Module, *Proceedings of the 25th European Photovoltaic Solar Energy Conference*, pp. 3508-3512, ISBN 3-936338-26-4, Valencia, Spain, September 2010

Dobson, K.D.; Visoly-Fisher, I.; Hodes, G. & Cahen, D. (2000). Stability of CdTe/CdS Thin-Film Solar Cells. *Solar Energy Materials and Solar Cells*, Vol.62, No.3, May 2000, pp. 295-325

Doni, A.; Dughiero, F. & Lorenzoni, A. (2010). A Comparison Between Thin Film and C-Si PV Technologies for MW Size Applications, *Proceedings of the 35th IEEE Photovoltaics Specialists Conference*, pp. 2380-2385, ISBN 978-1-4244-5890-5, Honolulu, USA, June 2010

Dunlop, E.D. & Halton, D. (2005). The Performance of Crystalline Silicon Photovoltaic Solar Modules After 22 Years of Continuous Outdoor Exposure. *Progress in Photovoltaics: Research and Applications*, Vol.14, No.1, June 2005, pp. 53-64

EPIA & Greenpeace. (2011). Solar Photovoltaic Energy Empowering the World, In: *Solar Generation 6*, 24.06.2011, Available from: http://www.greenpeace.org/international/en/publications/reports/Solar-Generation-6/

EPIA. (2010). 2010 Market Outlook, In: *EPIA Publications*, 24.06.2011, Available from: http://www.epia.org/publications/photovoltaic-publications-global-market-outlook.html

EPIA. (2011). Global Market Outlook for Photovoltaics Until 2015, In: *EPIA Publications*, 24.06.2011, Available from: http://www.epia.org/publications/photovoltaic-publications-global-market-outlook.html

Ferekides, C. & Britt, J. (1994). CdTe Solar Cells With Efficiencies Over 15%. *Solar Energy Materials and Solar Cells*, Vol.35, (September 1994), pp. 255-262

Fthenakis, V.M. (2004). Life Cycle Impact Analysis of Cadmium in CdTe Photovoltaic Production. *Renewable and Sustainable Energy Reviews*, Vol.8, (August 2004), pp. 303-334

Fthenakis, V.M. (2009). Sustainability of photovoltaics: The Case for Thin-Film Solar Cells. *Renewable and Sustainable Energy Reviews*, Vol.13, (December 2009), pp. 2746-2750

Fthenakis, V.M.; Fuhrmann, M.; Heiser, J.; Lanzirotti, A.; Fitts, J. & Wang, W. (2005). Emissions and Encapsulation of Cadmium in CdTe PV Modules during Fires. *Progress in Photovoltaics: Research and Applications*, Vol.13, (2005), pp. 713-723

Fthenakis, V.M.; Kim, H.C. & Alsema, E. (2008). Emissions from Photovoltaic Life Cycles. *Environmental Science & Technology*, Vol.42, No.6, (2008), pp. 2168–2174

Gabor, A.M.; Tuttle, J.R.; Albin, D.S.; Contreras, M.A.; Noufi, R. & Herman, A.M. (1994). High-Efficiency CuInxGa1−xSe2 Solar Cells Made From (Inx,Ga1−x)2Se3 Precursor Films. *Applied Physics Letters*, Vol.65, No.2, (July 1994), pp. 198-200

Gottschalg, R.; Betts, T.R.; Hohl-Ebinger, J.; Herrmann, W. & Müllejans, H. (2007). Effect of Spectral Mismatch on Power Rating Measurements – A Comparison of Indoor and Outdoor Measurements for Single and Multi-Junction Devices, *Proceedings of the 22nd European Photovoltaic Solar Energy Conference*, pp. 2621-2624, Milan, Italy, September 2007

Gottschalg, R.; Betts, T.R.; Infield, D.G. & Kearney, M.J. (2005). The Effect of Spectral Variations on the Performance Parameters of Single and Double Junction Amorphous Silicon Solar Cells. *Solar Energy Materials and Solar cells*, Vol.85, No.3, January 2005, pp. 415-428

Gottschalg, R.; Infield, D.G. & Kearney, M.J. (2003). Experimental Study of Variations of the Solar Spectrum of Relevance to Thin-Film Solar Cells. *Solar Energy Materials and Solar Cells*, Vol.79, No.4, September 2003, pp. 527-537

Green, M.A.; Emery, K.; Hishikawa, Y. & Warta, W. (2011). Solar Cell Efficiency Tables (version 37). *Progress in Photovoltaic: Research and Applications*, Vol.19, No.1, (January 2011), pp. 84–92

Green, M.A.; Emery, K.; Hishikawa, Y. & Warta, W. (2011). Solar Cell Efficiency Tables (version 38). *Progress in Photovoltaic: Research and Applications*, Vol.19, No.5, (August 2011), pp. 565-572

Grunow, P.; Preiss, A.; Koch, S. & Krauter, S. (2009). Yield and Spectral Effects of A-Si Modules, *Proceedings of the 24th European Photovoltaic Solar Energy Conference*, pp. 2846-2829, ISBN 3-936338-25-6, Hamburg, Germany, September 2009

GTM Research, (2011). Concentrating Photovoltaics 2011: Technology, Costs and Markets, In: *GTM Research*, 24.06.2010, Available from: http://www.greentechmedia.com/research/report/concentrating-photovoltaics-2011

Gueymard, C.; Myers, D. & Emery, K. (2002). Proposed Reference Irradiance Spectra for Solar Energy Systems Testing. *Solar Energy*, Vol.73, No.6, December 2002, pp. 443-467

Guillemoles, J.-F.; Kronik, L.; Cahen, D.; Rau, U.; Jasenek, A. & Schock, H.-W. (2000). Stability Issues of Cu(In,Ga)Se2-Based Solar Cells. *Journal of Physical Chemistry B*, Vol.104, No.20, April 2000, pp. 4849-4862

Hammond, R.; Srinivasan, D.; Harris, A.; Whitfield, K. & Wohlgemuth, J. (1997). Effects of Soiling on PV Module and Radiometer Performance, *Proceedings of the 26th IEEE Photovoltaics Specialists Conference*, pp. 1121-1124, ISBN 0-7803-3767-0, Anaheim, USA, September 1997

Heesen, H.; Pfatischer, R.; Herbort, V. & von Schwerin, R. (2010). Performance Evaluation of Thin-Film Technologies Based on Operating Data, *Proceedings of the 25th*

European Photovoltaic Solar Energy Conference, pp. 3766-3768, ISBN 3-936338-26-4, Valencia, Spain, September 2010

Hegedus, S. (2006). Thin Film Solar Modules: the Low Cost, High Throughput and Versatile Alternative to Si Wafers. *Progress in Photovoltaics: Research and Applications*, Vol.14, No.5, June 2006, pp. 393-411

Hirata, Y. & Tani, T. (1995). Output Variation of Photovoltaic Modules with Environmental Factors-I. The Effect of Spectral Solar Variation on Photovoltaic Module Output, *Solar Energy*, Vol.55, No.6, December 1995, pp. 463-468

Huld, T.; Sample, T. & Dunlop, E.D. (2009). A Simple Model for Estimating the Influence of Spectrum Variations on PV Performance, *Proceedings of the 24th European Photovoltaic Solar Energy Conference*, pp. 3385-3389, ISBN 3-936338-25-6, Hamburg, Germany, September 2009

Ibrahim, M.; Zinsser, B.; El-Sherif, H.; Hamouda, E.; Makrides, G.; Georghiou, G.E.; Schubert, M. & Werner, J.H. (2009). Advanced Photovoltaic Test Park in Egypt for Investigating the Performance of Different Module and Cell Technologies, *Proceedings of the 24th Symposium Photovoltaic Solar Energy*, Staffelstien, Germany, March 2009

Igalson, M.; Wimbor, M.; Wennerberg, J. (2002). The Change of the Electronic Properties of CIGS Devices Induced by the Damp Heat Treatment. *Thin Solid Films*, Vol.403-404, February 2002, pp. 320-324

Ikisawa, M.; Nakano, A.; Igari, S. & Terashima, H. (1998). Outdoor Exposure Tests of Photovoltaic Modules in Japan and Overseas. *Renewable Energy*, Vol.14, No.1-4, May-August 1998, pp. 95-100

Jasenek, A.; Rau, U.; Weinert, K.; Schock, H.W. & Warner, J.H. (2002). Illumination-Enhanced Annealing of Electron-Irradiated Cu(In,Ga)Se2 Solar Cells, *Proceedings of the 29th IEEE Photovoltaic Specialists Conference*, pp. 872-875, ISBN 0-7803-7471-1, New Orleans, USA, May 2002

Jordan, D.C. & Kurtz, S.R. (2010). Analytical Improvements in PV Degradation Rate Determination, *Proceedings of the 35th IEEE Photovoltaics Specialists Conference*, pp. 2688-2693, ISBN 978-1-4244-5890-5, Honolulu, USA, June 2010

Jordan, D.C.; Smith, R.M.; Osterwald, C.R.; Gelak, E. & Kurtz, S.R. (2010). Outdoor PV Degradation Comparison, *Proceedings of the 35th IEEE Photovoltaics Specialists Conference*, pp. 2694-2697, ISBN 978-1-4244-5890-5, Honolulu, USA, June 2010

JRC. (2010). PV Status Report 2010, In: *Scientific & Technical Reference on Renewable Energy and End-Use Energy Efficiency*, 24.06.2011, Available from: http://re.jrc.ec.europa.eu/refsys/

Kazmerski, L.L.; White, F.R. & Morgan, G.K. (1976). Thin-Film CuInSe2/CdS Heterojunction Solar Cells. *Applied Physics Letters*, Vol.29, No.4, (August 1976), pp. 268-271

Kenny, R.P.; Ionnides, A.; Mullejans, H.; Zaaiman W. & Dunlop, E.D. (2006). Performance of Thin Film PV Modules. *Thin Solid Films*, Vol.511-512, July 2006, pp. 663-672

King, D.; Boyson, W.E. & Kratochvyl, J.A. (2004). Photovoltaic Array Performance Model, In: *SAND2004-3535*, 24.06.2010, Available from: http://photovoltaics.sandia.gov/docs/PDF/King%20SAND.pdf

King, D.; Kratochvil, J.A. & Boyson, W.E. (1997). Measuring the Solar Spectral and Angle of Incidence Effects on Photovoltaic Modules and Solar Irradiance Sensors, *Proceedings of the 26th IEEE Photovoltaic Specialists Conference*, pp. 1113-1116, ISBN 0-7803-3767-0, Anaheim, USA, September 1997

King, D.L.; Kratochvil J.A. & Boyson, W.E. (2000). Stabilization and Performance Characteristics of Commercial Amorphous-Silicon PV Modules, *Proceedings of the 28th IEEE Photovoltaic Specialists Conference*, pp. 1446-1449, ISBN 0-7803-5772-8, Anchorage, USA, September 2000

King, D.L; Hansen, B.R.; Kratochvil, J.A. & Quintana, M.A. (1997). Dark Current-Voltage Measurements on Photovoltaic Modules as a Diagnostic or Manufacturing Tool, *Proceedings of the 26th IEEE Photovoltaic Specialists Conference*, pp. 1125-1128, ISBN 0-7803-3767-0, Anaheim, USA, September 1997

King, D.L; Kratochvil, J.A. & Boyson, W.E. (1997). Temperature coefficients for PV Modules and Arrays: Measurement Methods, Difficulties, and Results, *Proceedings of the 26th IEEE Photovoltaic Specialists Conference*, pp. 1183-1186, ISBN 0-7803-3767-0, Anaheim, USA, September 1997

Kymakis, E.; Kalykakis, S. & Papazoglou, T.M. (2009). Performance Analysis of a Grid Connected Photovoltaic Park on the Island of Crete. *Energy Conversion and Management*, Vol. 50, No. 3, March 2009, pp. 433–438

Lam, K.H.; Close, J. & Durisch, W. (2004). Modelling and Degradation Study on a Copper Indium Diselenide Module. *Solar Energy*, Vol.77, No.1, 2004, pp. 121-127

Lechner, P.; Geyer, R.; Haslauer, A.; Roehrl, T.; Lundszien, D.; Weber, C. & Walter, R. (2010). Long-Term Performance of ASI Tandem Junction Thin Film Solar Modules, *Proceedings of the 25th European Photovoltaic Solar Energy Conference*, pp. 3283-3287, ISBN 3-936338-26-4, Valencia, Spain, September 2010

Makrides, G.; Zinsser, B.; Georghiou, G.E., Schubert, M. & Werner, J.H. (2009). Error Sources in Outdoor Performance Evaluation of Photovoltaic Systems, *Proceedings of the 24th European Photovoltaic Solar Energy Conference*, pp. 3904-3909, ISBN 3-936338-25-6, Hamburg, Germany, September 2009

Makrides, G.; Zinsser, B.; Georghiou, G.E.; Schubert, M. & Werner, J.H. (2009). Temperature Behavior of Different Photovoltaic Systems Installed in Cyprus and Germany. *Solar Energy Materials & Solar Cells*, Vol.93, No.6-7, (June 2009), pp. 1095–1099

Makrides, G.; Zinsser, B.; Norton, M.; Georghiou, G.E.; Schubert, M. & Werner, J.H. (2010). Outdoor Performance Evaluation of Grid-Connected PV Technologies in Cyprus. *Journal of Energy and Power Engineering*, Vol.4, No.2, (February 2010), pp. 52–57

Makrides, G.; Zinsser, B.; Norton, M.; Georghiou, G.E.; Schubert, M. & Werner, J.H. (2010). Potential of Photovoltaic Systems in Countries with High Solar Irradiation. *Renewable and Sustainable Energy Reviews*, Vol.14, No.2, (February 2010), pp. 754-762

Malmström, J.; Wennerberg, J. & Stolt, L. (2003). A Study of the Influence of the Ga Content on the Long-Term Stability of Cu(In,Ga)Se2 Thin Film Solar Cells. *Thin Solid Films*, Vol.431-432 May 2003, pp. 436-442

Marion, B.; Adelstein, J.; Boyle K.; Hayden, H,; Hammond, B.; Fletcher, T.; Canada, B.; Narang, D.; Kimber, A.; Mitchell, L.; Rich, G. & Townsend, T. (2005).

Performance Parameters for Grid-Connected PV Systems, *Proceedings of the 31st IEEE Photovoltaics Specialists Conference*, pp. 1601-1606, ISBN 0-7803-8707-4, Lake Buena Vista, USA, January 2005

McMahon, T.J. (2004). Accelerated Testing and Failure of Thin-film PV Modules. *Progress in Photovoltaics: Research and Applications*, Vol.12, No.23, 2004, pp. 235–248

Merten, J. & Andreu, J. (1998). Clear Separation of Seasonal Effects on the Performance of Amorphous Silicon Solar Modules by Outdoor I/V-Measurements. *Solar Energy Materials and Solar Cells*, Vol.52, No.1-2, (March 1998), pp. 11-25

Meyer, E.L. & van Dyk, E.E. (2004). Assessing the Reliability and Degradation of Photovoltaic Module Performance Parameters. *IEEE Transactions on Reliability*, Vol. 53, No. 1, March 2004, pp 83-92

Meyers P.V. (2006). First Solar Polycrystalline CdTe Thin Film PV, *Proceedings of the 4th IEEE World Conference on Photovoltaic Energy Conversion*, pp. 2024-2027, ISBN 1-4244-0017-1, Waikoloa, USA, May 2006

Mohring, H.-D.M, & Stellbogen, D. (2008). Annual Energy Harvest of PV Systems– Advantages and Drawbacks of Different PV Technologies, *Proceedings of the 23rd European Photovoltaic Solar Energy Conference*, pp. 2781-2785, ISBN 3-936338-24-8, Valencia, Spain, September 2008

Mrig, L. & Rummel S. (1990). Outdoor Stability of Performance of CIS and CdTe Photovoltaic Modules at SERI. *Proceedings of the 21st IEEE Photovoltaic Specialist Conference*, pp. 1038-1039, Kissimmee, USA, May 1990

Myers, D.R.; Emery, K. & Gueymard, C. (2002). Terrestrial Solar Spectral Modeling Tools and Applications for Photovoltaic Devices, *Proceedings of the 29th IEEE Photovoltaic Specialists Conference*, pp. 1683-1686, ISBN 0-7803-7471-1, New Orleans, USA, May 2002

Norton, M.; Dobbin, A. & Georghiou, G.E. (2011). Solar Spectrum Prediction and Comparison with Measurements, *Proceedings of the International Conference on Concentrating Photovoltaic Systems*, Las Vegas, USA, April 2011

Oerlikon Solar. (2010). Oerlikon Solar Breaking Two World Records: Lowest Module Production Cost and Highest Lab Cell Efficiency, In: *Press Releases Archive 2010*, 24.06.2011, Available from: http://www.oerlikon.com/ecomaXL/index.php?site=OERLIKON_EN_archive_2010_detail&udtx_id=7720

Osterwald, C.R.; Adelstein, J.; del Cueto, J.A.; Kroposki, B.; Trudell, D. & Moriarty, T. (2006). Comparison of Degradation Rates of Individual Modules Held at Maximum Power, *Proceedings of the 4th IEEE World Conference on Photovoltaic Energy Conversion*, pp. 2085-2088, ISBN 1-4244-0017-1, Waikoloa, USA, May 2006

Osterwald, C.R.; Anderberg, A.; Rummel, S. & Ottoson, L. (2002). Degradation Analysis of Weathered Crystalline-Silicon PV Modules, *Proceedings of the 29th IEEE Photovoltaic Specialists Conference*, pp. 1392-1395, ISBN 0-7803-7471-1, New Orleans, USA, May 2002

Paretta, A.; Sarno, A. & Vicari, L. (1998). Effects of Solar Irradiation Conditions on the Outdoor Performance of Photovoltaic Modules. *Optics Communication*, Vol.153, No.1-3, (July 1998), pp. 153-163

Pern, F.J.; Czanderna, A.W.; Emery, K.A. & Dhere, R.G. (1991). Weather Degradation of EVA Encapsulant and the Effect of its Yellowing on Solar Cell Efficiency, *Proceedings of the 22nd IEEE Photovoltaic Specialists Conference*, pp. 557-561, ISBN 0-87942-636-5, Las Vegas, USA, October 1991

Powell, R.C.; Sasala, R.; Rich, G.; Steele, M.; Bihn, K.; Reiter, N.; Cox, S. & Dorer, G. (1996). Stability Testing of CdTe/CdS Thin-Film Photovoltaic Modules, *Proceedings of the 25th IEEE Photovoltaic Specialists Conference*, pp. 785-788, ISBN 0-7803-3166-4, Washington, USA, May 1996

Quintana, M.A.; King, D.L.; McMahon, T.J. & Osterwald, R.C. (2002). Commonly Observed Degradation in Field-Aged Photovoltaic Modules, *Proceedings of the 29th IEEE Photovoltaic Specialists Conference*, pp. 1436-1439, ISBN 0-7803-7471-1, New Orleans, USA, May 2002

Randall J.F. & Jacot, J. (2003). Is AM1.5 Applicable in Practice? Modelling Eight Photovoltaic Materials With Respect to Light Intensity and Two Spectra. *Renewable Energy*, Vol.28, No.12, (October 2003), pp. 1851–1864

Ransome, S.J. & Wohlgemuth, J.H. (2000). Predicting kWh/kWp Performance for Amorphous Silicon Thin Film Modules, *Proceedings of the 28th IEEE Photovoltaic Specialists Conference*, pp. 1505-1508, ISBN 0-7803-5772-8, Anchorage, September 2000

Reich, N.H.; van Sark, W.G.J.H.M.; Alsema, E.A.; Lof, R.W.; Schropp, R.E.I.; Sinke, W.C. & Turkenburg, W.C. (2009). Crystalline Silicon Cell Performance at Low Light Intensities. *Solar Energy Materials and Solar Cells*, Vol.93, No.9, (September 2009), pp. 1471–1481

Sanchez-Friera, P.; Piliougine, M.; Pelaez, J.; Carretero, J. & Sidrach M. (2011). Analysis of Degradation Mechanisms of Crystalline Silicon PV Modules After 12 Years of Operation in Southern Europe. *Progress in Photovoltaics: Research and Applications*, January 2011

Schmidt, M.; Braunger, D.; Schäffler, R.; Schock, H.W. & Rau, U. (2000). Influence of Damp Heat on the Electrical Properties of Cu(In,Ga)Se2 Solar Cells. *Thin Solid Films*, Vol.361-362, February 2000, pp. 283-287

Schumann, A. (2009). Irradiance Level Characteristics of PV Modules and the Need for Improved Data Quality, *Proceedings of the 24th European Photovoltaic Solar Energy Conference*, pp. 3468-3470, ISBN 3-936338-25-6, Hamburg, Germany, September 2009

Shah, A.; Torres, P.; Tscharner, R.; Wyrach, N. & Keppner, H. (1999). Photovoltaic Technology: The Case of Thin-Film Solar Cells. *Science*, Vol.285, No.5428, (July 1999), pp. 692-698

Som, A.K. & Al-Alawi, S.M. (1992). Evaluation of Efficiency and Degradation of Mono- and Polycrystalline PV Modules Under Outdoor Conditions. *Renewable Energy*. Vol.2, No.1, February 1992, pp. 85-91

Staebler, D.L. & Wronski, C.R. (1977). Reversible Conductivity Charges in Discharge-Produced Amorphous Si. *Applied Physics Letters*, Vol.31, No.4, (August 1977), pp. 292–294

Stutzmann, M.; Jackson, W.B. & Tsai, C.C. (1985). Light-Induced Metastable Defects in Hydrogenated Amorphous Silicon: A Systematic Study. *Physical Review B*, Vol.32, No.1, July 1985, pp. 23-47

Sutterlüti, J.; Sinicco, I.; Hügli, A.; Hälker, T. & Ransome, S. (2009). Outdoor Characterization and Modelling of Thin-Film Modules and Technology Benchmarking, *Proceedings of the 24th European Photovoltaic Solar Energy Conference*, pp. 3198-3205, ISBN 3-936338-25-6, Hamburg, Germany, September 2009

Suzuki, R.; Kawamura, H.; Yamanaka, S.; Ohno, H. & Naito, K. (2002). Loss Factors Affecting Power Generation Efficiency of a PV Module, *Proceedings of the 29th IEEE Photovoltaic Specialists Conference*, pp. 1557-1560, ISBN 0-7803-7471-1, New Orleans, Louisiana, May 2002

Ullal, H.S.; Zweibel, K. & von Roedem, B. (1997). Current Status of Polycrystalline Thin-Film PV Technologies, *Proceedings of the 26th IEEE Photovoltaic Specialist Conference*, pp. 301-305, ISBN 0-7803-3767-0, Anaheim, USA, September 1997

Virtuani, A.; Mullejans, H. & Dunlop, E.D. (2011). Comparison of Indoor and Outdoor Performance Measurements of Recent Commercially Available Solar Modules. *Progress in Photovoltaics: Research and Applications*, Vol.19, No.1, January 2011, pp. 11-20

Virtuani, A.; Pavanello, D. & Friesen, G. (2010). Overview of Temperature Coefficients of Different Thin Film Photovoltaic Technologies, *Proceedings of the 25th European Photovoltaic Solar Energy Conference*, pp. 4248-4252, ISBN 3-936338-26-4, Valencia, Spain, September 2010

Wenham, S.R.; Green, M.A. & Watt, M.E. (2007). *Applied Photovoltaics*, (Second edition), Earthscan, ISBN 978-1-84407-401-3, London, UK

Wolden, C.A.; Kurtin, J.; Baxter, J.B.; Repins, I.; Shaheen, S.E.; Torvik, J.T.; Rockett, A.A.; Fthenakis, V.M. & Aydil, E.S. (2011). Photovoltaic Manufacturing: Present Status, Future Prospects, and Research Needs. *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films*, Vol.29, No.3, (May 2011), pp. 030801-030801-16, ISSN 0734-2101

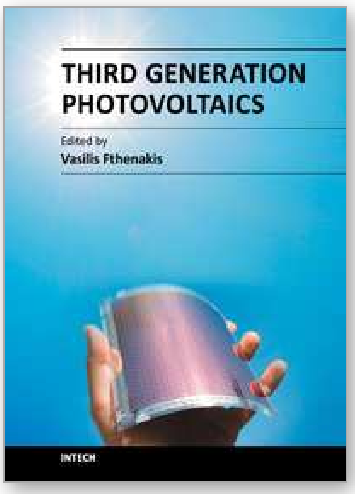
Zanesco, I. & Krenziger, A. (1993). The Effects of Atmospheric Parameters on the Global Solar Irradiance and on the Current of a Solar Cell. *Progress in Photovoltaics: Research and Applications*, Vol.1, No.3, July 1993, pp. 169-179

Zdanowicz, T.; Rodziewicz, T. & Waclawek, M.Z. (2003). Effect of Airmass Factor on the Performance of Different Type of PV Modules, *Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion*, pp. 2019-2022, ISBN 4-9901816-0-3, Osaka, Japan, May 2003

Zinsser, B.; Makrides, G.; Schmitt, W.; Georghiou, G.E. & Werner, J.H. (2007). Annual Energy Yield of 13 Photovoltaic Technologies in Germany and Cyprus, *Proceedings of the 22nd European Photovoltaic Solar Energy Conference*, pp. 3114-3117, Milan, September 2007

Zinsser, B.; Makrides, G.; Schubert, M.; Georghiou, G.E. & Werner, J.H. (2009). Temperature and Irradiance Effects on Outdoor Field Performance, *Proceedings of the 24th European Photovoltaic Solar Energy Conference*, pp. 4083-4086, ISBN 3-936338-25-6, Hamburg, Germany, September 2009

Zinsser, B.; Makrides, G.; Schubert, M.B.; Georghiou, G.E. & Werner, J.H. (2010). Rating of Annual Energy Yield More Sensitive to Reference power Than Module Technology, *Proceedings of the 35th IEEE Photovoltaics Specialists Conference*, pp. 1095-1099, ISBN 978-1-4244-5890-5, Honolulu, USA, June 2010



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