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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<sup>2</sup>, 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  $\mu\text{m}$  to 200  $\mu\text{m}$  and in parallel the increase in area from 100  $\text{cm}^2$  to 240  $\text{cm}^2$ . 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  $\mu\text{m}$  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  $\text{cm}^2$  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  $\mu\text{m}$  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/ $\mu$ c-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 ( $\mu$ c-Si) layer of the order of 2  $\mu$ m onto the substrate. The application of the  $\mu$ c-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  $\mu\text{m}$  thickness, hence films of only 1 - 3  $\mu\text{m}$  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 ( $\text{CuInSe}_2$ ) often called CIS, copper-gallium-diselenide ( $\text{CuGaSe}_2$ ) called CGS, their mixed alloys copper-indium gallium-diselenide ( $\text{Cu(In,Ga)Se}_2$ ) called CIGS and copper-indium-disulfide ( $\text{CuInS}_2$ ). 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 ( $\mu\text{m}$ ) | Area ( $\text{m}^2$ )              | Efficiency (%) | Surface area for 1 $\text{kW}_p$ system ( $\text{m}^2$ ) |
|------------------------|--------------------------------------|------------------------------------|----------------|--|
| Mono-c-Si              | 200                                  | 1.4 - 1.7 (typical)                | 14 - 20        | $\sim 7$   |
| Multi-c-Si             | 160                                  | 1.4 - 1.7 (typical)<br>2.5 (up to) | 11 - 15        | $\sim 8$   |
| a-Si                   | 1                                    | $\sim 1.5$                         | 4 - 8          | $\sim 15$  |
| a-Si/ $\mu\text{c-Si}$ | 2                                    | $\sim 1.4$                         | 7 - 9          | $\sim 12$  |
| CdTe                   | $\sim 1 - 3$                         | $\sim 0.6 - 1$                     | 10 - 11        | $\sim 10$  |
| CIGS                   | $\sim 2$                             | $\sim 0.6 - 1$                     | 7 - 12         | $\sim 10$  |

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<sub>p</sub> 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,  $\eta$ , 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<sub>p</sub>), 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<sub>p</sub>), to allow for comparison between the different installed PV technologies (Marion et.al, 2005). The final yield,  $Y_f$ , is given by:

$$Y_f = \frac{E_{dc}}{P_0} \quad (1)$$

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

$$\eta = \frac{E_{dc}}{H \times A} \quad (2)$$

where  $H$  (kWh/m<sup>2</sup>) is the total plane of array irradiation and  $A$  (m<sup>2</sup>) 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:

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

where  $\eta_{STC}$  (%) 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<sup>2</sup> (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<sup>2</sup> 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<sup>2</sup> 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<sup>2</sup> 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  $200 \text{ W/m}^2$  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  $200 \text{ W/m}^2$  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  $25 \text{ }^\circ\text{C}$  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; Sutterlütli 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  $-0.45 \text{ \%}/\text{K}$  (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  $-0.25 \text{ \%}/\text{K}$  (Dittmann et al., 2010). In addition, a-Si shows the lowest power temperature coefficient of up to approximately  $-0.20 \text{ \%}/\text{K}$  (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 & Wohlgenuth, 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/ $\mu$ c-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  $\pm 1.5$  % (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 migration 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; Degraeve 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 et 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  $1000 \text{ W/m}^2$ , air temperature of  $20 \text{ }^\circ\text{C}$  and wind speed of  $1 \text{ m/s}$ . 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 $\text{SnO}_2$ from soda-lime glass           | $I_{sc}$ decreases and $R_{series}$ increases                    | Na ion migration to $\text{SnO}_2$ /glass interface  |
| f. De-adhesion of back metal contact                         | $I_{sc}$ 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 segregation)  |
| 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  $0.7 \text{ %/year}$  while the reported median was  $0.5 \text{ %/year}$  (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/m <sup>2</sup> ) |
|-----------------------|---|
| 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/m<sup>2</sup>. During the first three years, the highest amount of solar irradiation occurred within the range 801 - 900 W/m<sup>2</sup> while in the fourth year within the range 901 - 1000 W/m<sup>2</sup>.

| Solar Irradiance (W/m <sup>2</sup> ) | 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<sub>p</sub> while during the second year of operation and for the same systems the average dc energy yield was 1769 kWh/kW<sub>p</sub>, 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<sub>p</sub> and 1658 kWh/kW<sub>p</sub> 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 <sub>p</sub> ) |             |             |             |
|---------------------------------|---|-------------|-------------|-------------|
|                                 | 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 Suntechnics 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<sup>2</sup> while during the second year it was 2606 kWh/m<sup>2</sup> (Makrides et al., 2010). Subsequently, during the third and fourth year the solar irradiation collected by the tracker was 2510 kWh/m<sup>2</sup> and 2483 kWh/m<sup>2</sup> respectively.

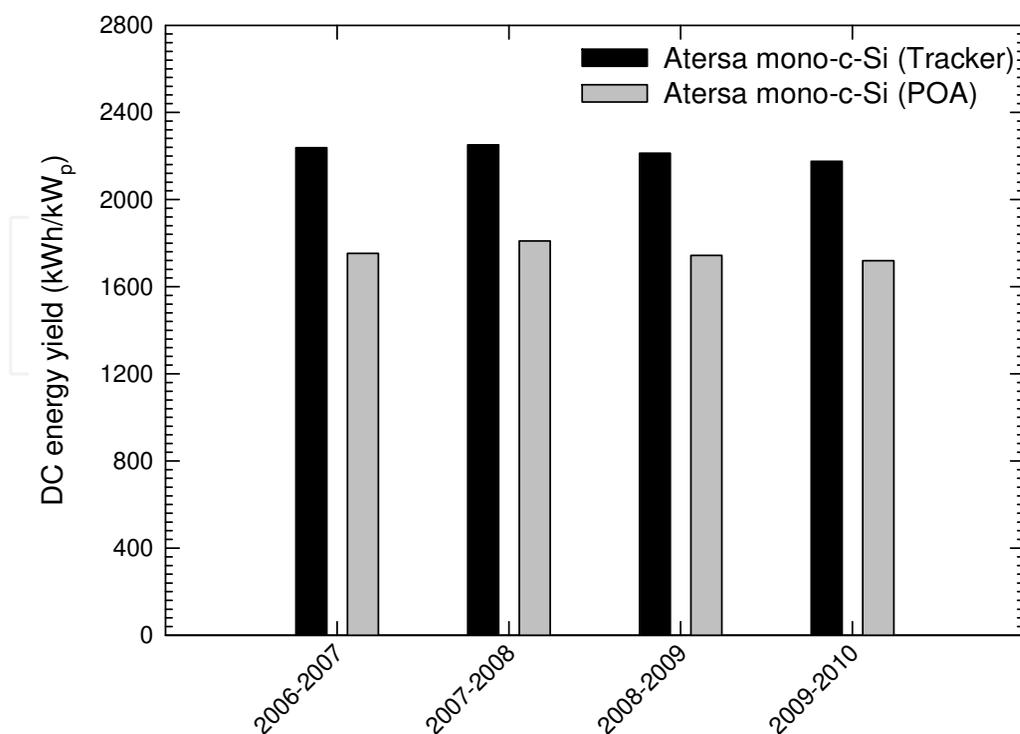


Fig. 1. Comparison of the annual dc energy yield of the tracker and fixed-plane Atersa mono-c-Si systems over the period June 2006 - June 2010.

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

| System                          | Normalized AC Energy Yield (kWh/kW <sub>p</sub> ) |             |             |             |
|---------------------------------|---|-------------|-------------|-------------|
|                                 | 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-FI/MC) | 1588  | 1642        | 1575        | 1552        |
| Schott Solar (ASE-260-DG-FI)    | 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<sup>2</sup>, 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.

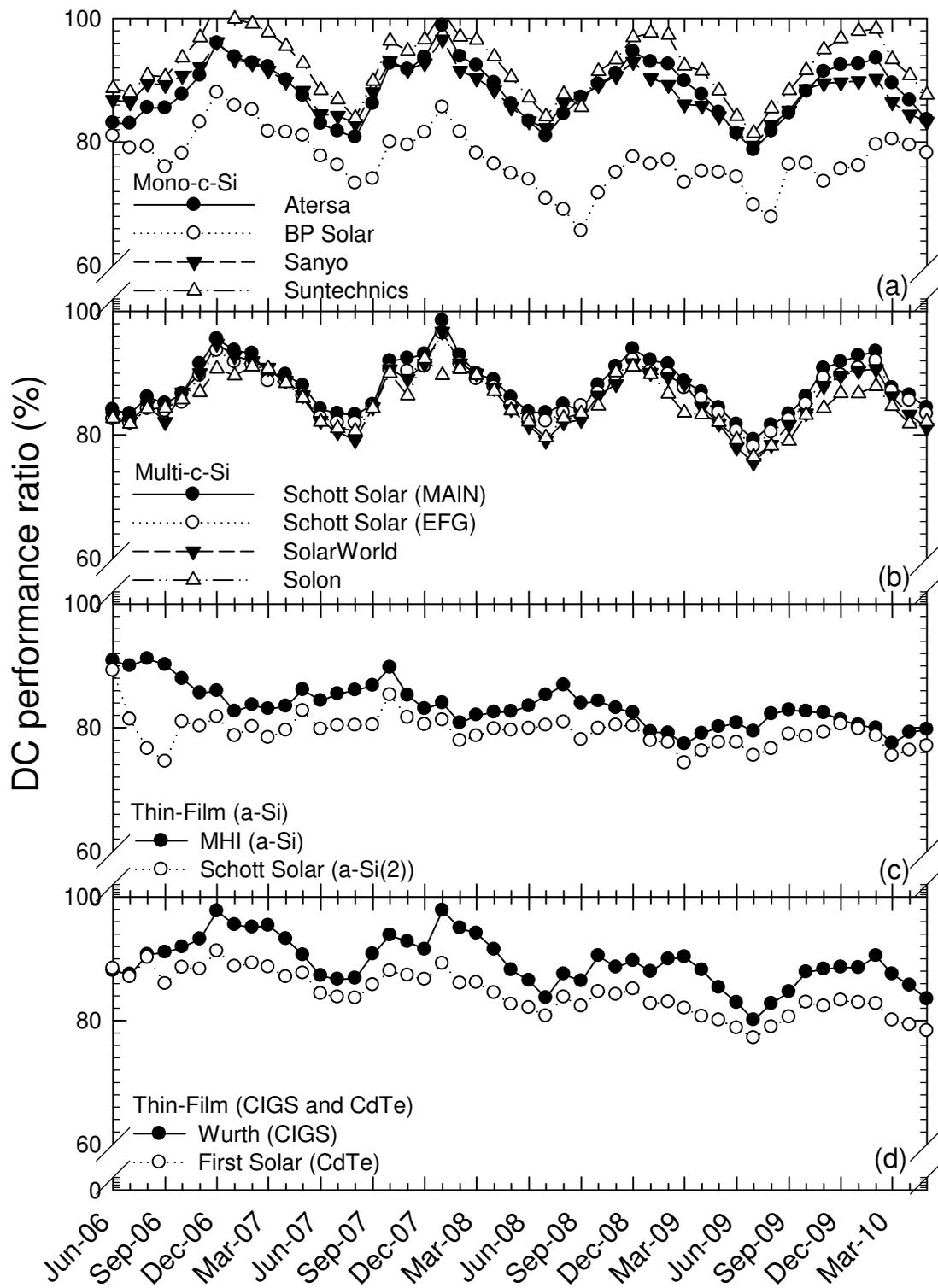


Fig. 2. Monthly average dc PR of installed PV systems over the period June 2006 - June 2010 in Nicosia, Cyprus.

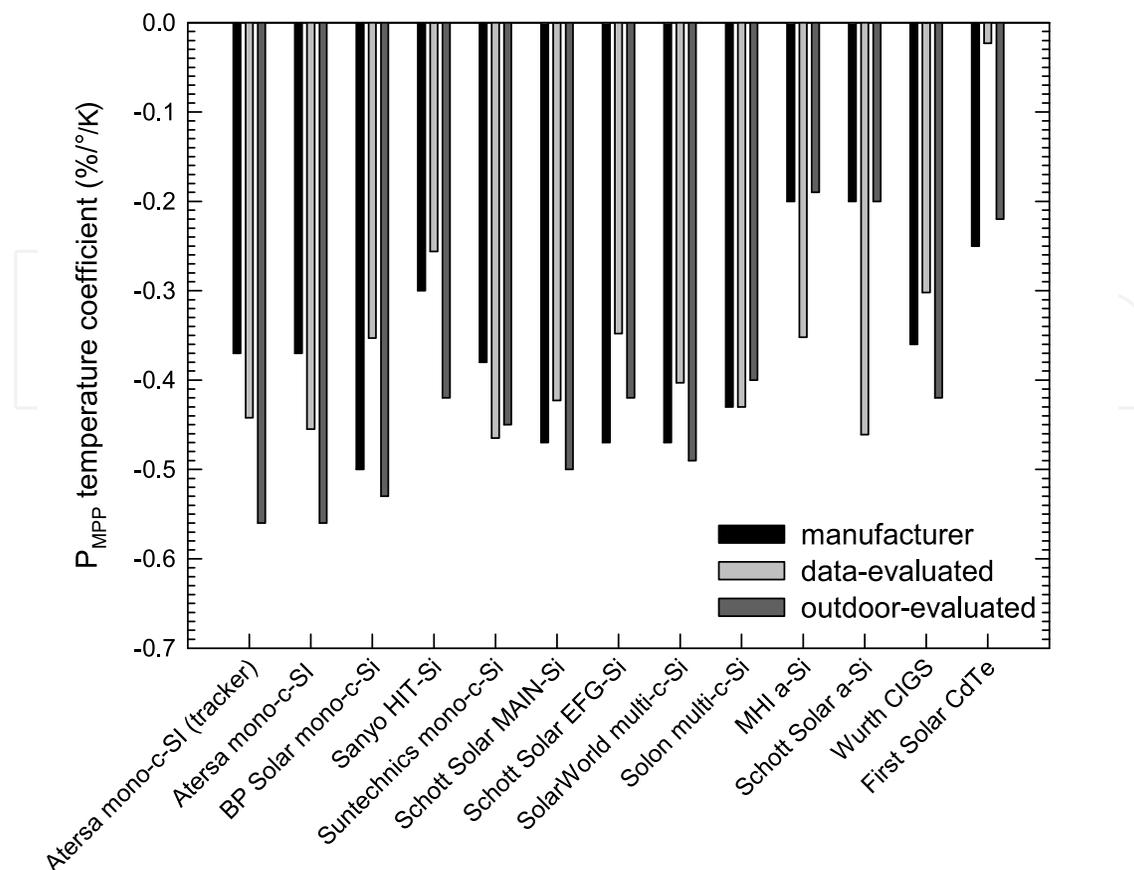


Fig. 3. Comparison of the MPP power temperature coefficients ( $\gamma_{PMPP}$  %/K) obtained by the two methods outlined above (outdoor measurements and data analysis) and the manufacturers' data for the installed systems.

#### 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  $\pm 3\%$  for c-Si PV modules, and  $\pm 5\%$  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 ( $\text{kWh}/\text{kW}_p$ ) to the rated power (Zinsser et al., 2010).

By considering an uncertainty of  $\pm 3\%$  due to the STC power and a  $\pm 2\%$  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 PV location. Therefore, there is a high need for low uncertainties in the power tolerance of PV modules.

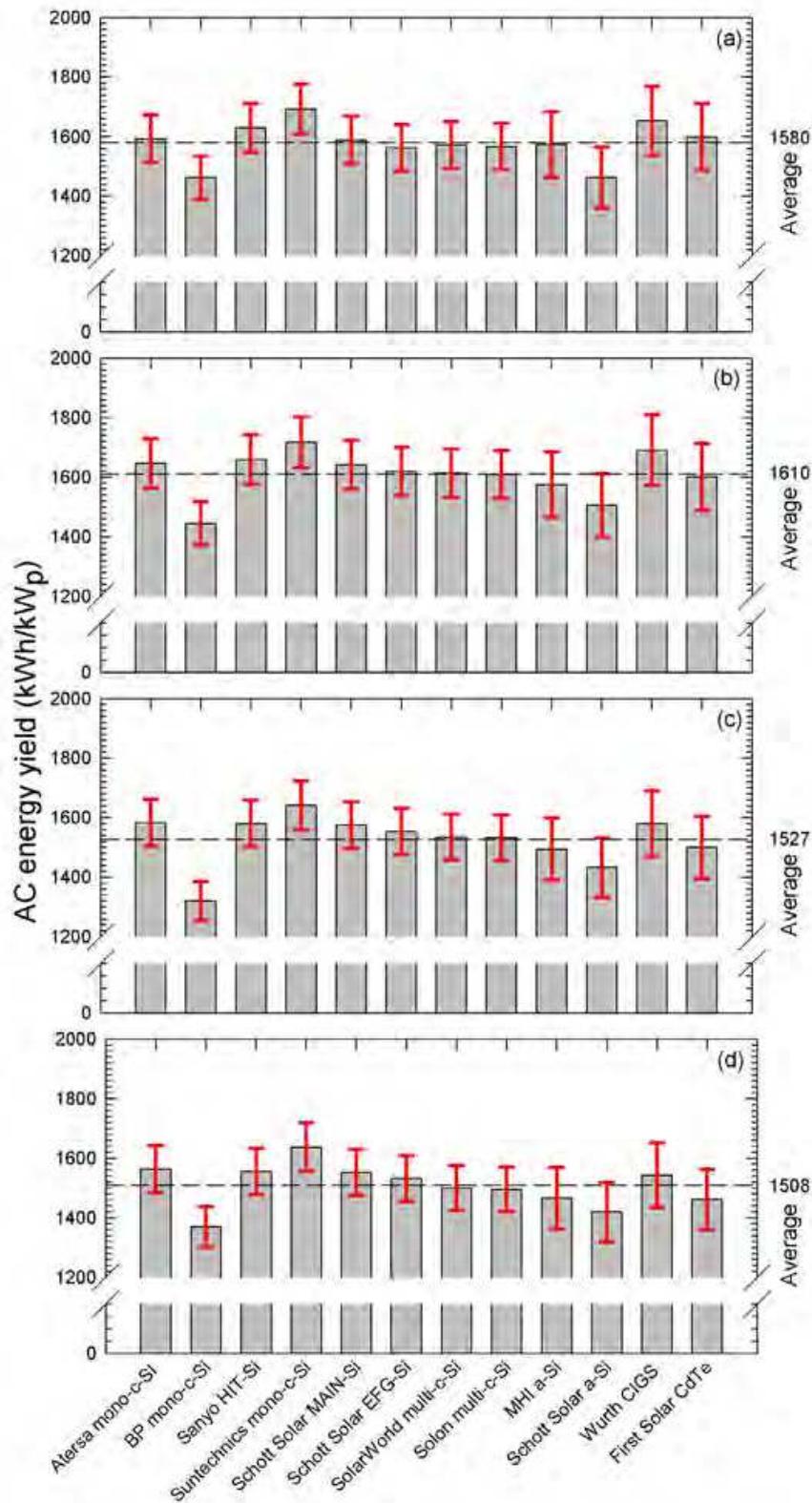


Fig. 5. Annual ac energy yield normalized to rated power over the period a) June 2006 - June 2007, b) June 2007 - June 2008, c) June 2008 - June 2009 and d) June 2009 - June 2010. The error bars represent the associated power rating and measurement uncertainty.

## 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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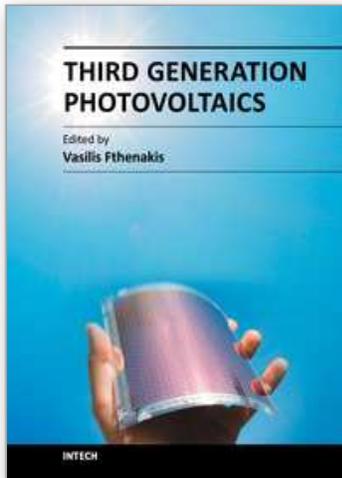
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### **Third Generation Photovoltaics**

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Photovoltaics have started replacing fossil fuels as major energy generation roadmaps, targeting higher efficiencies and/or lower costs are aggressively pursued to bring PV to cost parity with grid electricity. Third generation PV technologies may overcome the fundamental limitations of photon to electron conversion in single-junction devices and, thus, improve both their efficiency and cost. This book presents notable advances in these technologies, namely organic cells and nanostructures, dye-sensitized cells and multijunction III/V cells. The following topics are addressed: Solar spectrum conversion for photovoltaics using nanoparticles; multiscale modeling of heterojunctions in organic PV; technologies and manufacturing of OPV; life cycle assessment of OPV; new materials and architectures for dye-sensitized solar cells; advances of concentrating PV; modeling doped III/V alloys; polymeric films for lowering the cost of PV, and field performance factors. A panel of acclaimed PV professionals contributed these topics, compiling the state of knowledge for advancing this new generation of PV.

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