# Superior Energy Yields of *UNI-SOLAR®* Triple Junction Thin Film Silicon Solar Cells compared to Crystalline Silicon Solar Cells under Real Outdoor Conditions in Western Europe

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ABSTRACT: For many years, amorphous silicon photovoltaic modules have had difficulties to establish themselves in the grid-connected PV-market. Causes for this lack of market acceptance of first generation amorphous silicon PV modules were their relatively low conversion efficiencies, unstable power and not well understood outdoor characteristics. Various manufacturers of amorphous silicon modules have resolved these initial problems by enhancing the efficiencies of their cells, while at the same time improving the long-term stability of the products. Still, the outdoor behaviour of amorphous silicon modules is not well understood by many users, even by insiders of the PV-community. Results of this study will show that new generation multi-junction amorphous silicon modules, and in particular *UNI-SOLAR®* modules based on the Triple Junction solar cells, perform excellent under western European climatic conditions, with yields and performance ratios significantly higher than all present crystalline silicon technologies. This effect is especially pronounced under low light conditions and under non-ideal orientations. The enhanced outdoor performance, up to 20 % higher on a yearly kWh/kWp base, can be attributed to the higher sensitivity for low light conditions and for diffuse light, better performance at high temperatures and improved shadow tolerance of *UNI-SOLAR®* modules. Keywords: Monitoring – 1: Multi-junction Solar Cell – 2: Performance – 3

## 1. INTRODUCTION

Photovoltaic modules are sold with their peak power performance (Wp) tested under laboratory conditions (STC): i.e. under a very high and direct irradiation (1000 W/m²), module temperature of 25°C, and only one type of solar spectrum (AM1.5: mainly direct irradiation). Under real outdoor conditions, this peak power is seldom achieved, since module temperature usually is more in the range of 40-60°C under illumination (especially true for modules that are building integrated), the hours of 1000 W/m² irradiation is only about 1 % of total sun-hours and the spectral and specular content of the solar spectrum change continuously with varying climatic conditions. Diffuse light for instance dominates when the sky is clouded or during mornings and evenings. In Northern and Central Europe, the majority of solar irradiation comes from diffuse light (more than 50 % of all solar irradiation), and even in Madrid, the diffuse part is still 33 %. Customers buying photovoltaic modules are interested in high-energy yields per purchased Watt peak-power over a certain time period of a PV-system in true outdoor conditions. This is especially relevant in countries where there are high feed-in tariffs per kWh produced available such as in Germany or Spain. In order to predict what will be the energy output of a PV-module or a PV-system with a certain nominal power, it is necessary that behaviour of the modules under various climatic conditions is well known.

We will demonstrate in this article that *UNI-SOLAR®* modules produce more energy than could be expected from their nominal power and STC efficiency. *UNI-SOLAR®* modules actually perform better than all crystalline silicon and other thin film counterparts under real outdoor conditions in Western-European climates (higher kWh energy production per kWp purchased). It will be shown that this enhanced performance is especially pronounced under low light conditions, non-ideal orientations, and in conditions were module temperatures are high (e.g. in BIPV systems).

## 2. *UNI-SOLAR®* TRIPLE JUNCTION CELLS

All *UNI-SOLAR®* photovoltaic modules use the unique Triple Junction solar cells of United Solar System Corp. This Triple Junction technology provides unprecedented levels of efficiency and stability for amorphous silicon solar cells (stabilised aperture area cell efficiency of 7.0-7.5 %). Each cell is composed of three semiconductor junctions stacked on top of each other. The bottom cell absorbs the red light, the middle cell the green/yellow light and the top cell absorbs the blue light. This spectrum splitting capability is one of the keys to higher efficiencies and higher energy output, especially at lower irradiation levels and under diffuse light. The cells are produced in a unique roll-to-roll vacuum deposition process on a continuous roll of stainless steel sheet, employing only a fraction of the materials and energy of the production of standard crystalline silicon solar cells. The result is a flexible, light weight solar cell. The solar cells are encapsulated in UV-stabilised and weather-resistant polymers. The polymer encapsulation includes EVA and the fluoro-polymer TEFZEL® (a DuPont film) on the front side. The resulting modules are exceptionally durable. By-pass diodes are connected across *each* cell, allowing the modules to produce power even when partially shaded. *UNI-SOLAR®* modules are sold with a 20-year power warranty on 80 % of nominal power. Figure 1 demonstrates the excellent stability of *UNI-SOLAR®* modules with Triple Junction Solar Cells over a 3-year period (Triple Junction technology was introduced at the end of 1997). As can be seen in figure 1, small seasonal variations occur in the conversion efficiency. This periodic variation is the result of two competing processes during summer months: a deterioration of the semiconductor quality at higher operating temperatures and the annealing at those higher temperatures of light induced defects in the material, created by the Staebler-Wronski-effect, which repairs light induced defects again.

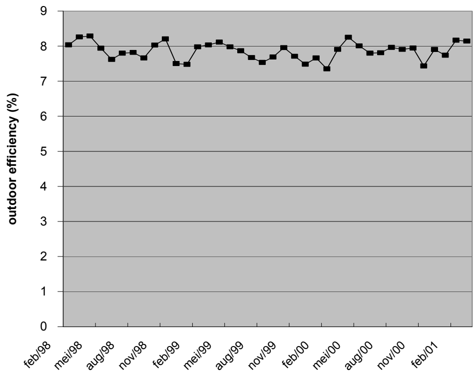


Fig. 1 – Outdoor cell efficiency of a *UNI-SOLAR®* module measured by Forschungszentrum Jülich from February 1998 to February 2001. Data by courtesy of FZ Jülich

## 3. MODULE MEASUREMENTS

Several European test centres (e.g. ECN in the Netherlands and TISO in Switzerland) have recently performed comparative studies on the outdoor performance of PV-modules from different manufacturers and with various technologies (mono- and poly-c-Si and various thin film technologies). In the ECN study [1], the outdoor sensitivity to various illumination levels has been measured and the temperature behaviour of the modules has been determined. This ECN-study shows that *UNI-SOLAR®* PV modules perform more than 40 % better at low light conditions (50 - 100 W/m²), than all present crystalline technologies (figure 2). Whereas for all c-Si modules and other thin film technologies the outdoor efficiency rapidly decreases below 300 W/m², the efficiency of *UNI-SOLAR®* modules shows a constant increase up to values as low as 50 W/m². The outdoor efficiency at 100 W/m² is more than 25 % higher than the STC-efficiency. In Northern and Central European climates, where low light conditions and diffuse light prevails, this enhanced low light sensitivity results in higher yearly energy output when normalised to Wp purchased power.

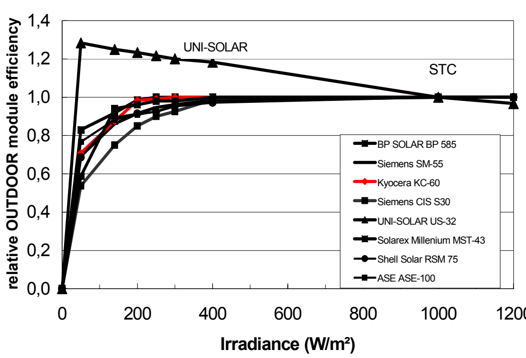


Fig 2 – Influence of irradiance on the relative outdoor module efficiency of various module types measured by ECN (see ECN report [1]). Module efficiency is normalised to the STC-value at 1000 W/m².

Another important aspect is the temperature dependence of the module characteristics. Crystalline silicon modules show a linear decrease of power output for increasing module temperature with a temperature coefficient for maximum power of about - 0.4 to - 0.5 %/°C. This means that at high ambient temperatures under full illumination (typical module temperature of 60°C), a crystalline silicon module of 100 Wp will exhibit an effective power of just 83-86 Watt, which means a power loss of about 15 %. For amorphous silicon modules this power loss at high operating temperatures is much less. The temperature behaviour of *UNI-SOLAR®* modules is also not linear. Outdoor measurements at TISO in Lugano [2] have shown that the power output of *UNI-SOLAR®* panels displays no temperature dependency for illumination levels below 600 W/m². For higher illumination levels (900-1100 W/m²) the effective power starts to drop only at ambient temperatures above 25°C and only very slowly (figure 3). Note that an effective power of 61 Watt was measured at TISO for a *UNI-SOLAR®* US-64 panel of 64 Wp nominal power at 1000 W/m² illumination and at an ambient temperature of 30°C (a loss in power of only 5%).

Knowing the outdoor characteristics of the various modules under various climatic conditions, an annual energy production yield can be determined for a certain PV-module. This has been done by simulations for a typical Dutch climate (ECN-study [1]) and by measurements over a 15-month period for a southern Swiss climate (TISO-study [2]). Table I shows the values of the DC-yields and performance ratios of the ECN study, while Table II exhibits the same values for the TISO measurements. It is striking to see that these independent results (modules were anonymously acquired on the free market) demonstrate that for both climatic conditions all amorphous silicon modules perform better than their crystalline silicon counterparts. The *UNI-SOLAR®* modules in these tests have the highest yield figures and performance ratios, 12 to 15% above the best c-Si module. This can be explained by their excellent low light level efficiency compared to the STC-efficiency and their insensitivity to temperature influences. Though the absolute value of the DC-yield must be taken with care (these are only single module measurements and do not include statistical variations of production processes, nor mismatch losses in string connections, and inverter losses), it does say however something in a relative sense.

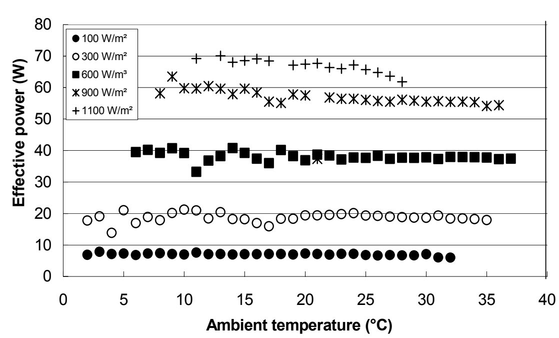


Fig 3 – Influence of ambient temperature and irradiance of a *UNI-SOLAR®* US-64 module as measured by TISO from March 2000- May 2001. Data of TISO [2].

Table I - Simulated yearly DC-yields and performance ratios (PR) for various modules determined by measured data of temperature and illumination behaviour of modules under Dutch outdoor conditions. See ECN report [1].

| Manufacturer and Type | Solar Cell Technology | STC power (Wp) | DC–yield (kWh/kWp/y) | PR (%) |
|---|---|---|---|---|
| *UNI-SOLAR*® US-32 | a-Si TJ | 32 | 1164 | 95 |
| FEE A13P | a-Si SJ | 12 | 1084 | 88 |
| BP Solar MST 43 | a-Si DJ | 43 | 1001 | 81 |
| BP Solar BP585 | mc-Si | 85 | 977 | 80 |
| Kyocera KC-60 | pc-Si | 60 | 964 | 79 |
| Siemens Solar SM-55 | mc-Si | 55 | 963 | 79 |
| ASE ASE-100 | pc-Si | 100 | 966 | 79 |
| Shell Solar RSM75 | pc-Si | 73 | 961 | 78 |
| Siemens Solar S-30 | CIGS | 30 | 930 | 76 |

Table II – Measured DC-yield and performance ratio (PR) for various modules in Lugano (CH) over the period March 2000 - May 2001 (cycle 7). Data courtesy of TISO.

| Manufacturer and Type | Technology | STC power (Wp) | DC–yield (kWh/kWp/y) | PR (%) |
|---|---|---|---|---|
| *UNI-SOLAR*® US-64 | a-Si TJ | 64 | 1341 | 93 |
| Siemens Solar ST40 | CIGS | 38 | 1264 | 88 |
| Duna Solar DS40 | a-Si DJ | 40 | 1246 | 86 |
| ASE 100GTFT | mc-Si | 100 | 1186 | 82 |
| Kyocera KC-60 | pc-Si | 60 | 1151 | 80 |
| Siemens Solar SM-55 | mc-Si | 55 | 1146 | 79 |
| Shell Solar RSM50 | pc-Si | 49 | 1139 | 79 |
| Photowatt PW100 | pc-Si | 91 | 1131 | 78 |
| Eurosolare M500A | pc-Si | 55 | 1069 | 74 |
| BP Solar BP275F | mc-Si | 75 | 1065 | 74 |
| GPV GPV75P | mc-Si | 75 | 1036 | 72 |
| BP Solar MSX83 | pc-Si | 83 | 1024 | 71 |
| Atlantis Sunslates | mc-S | 12,5 | 1004 | 70 |
| Atersa APX90 | mc-Si | 90 | 892 | 62 |

## 4. PV-SYSTEMS WITH *UNI-SOLAR*® MODULES

In order to get more statistically relevant data, larger PV-systems over longer time frames have been monitored. As is very often the case with all PV-systems, the ideal orientation and installation is very difficult to implement due to all kinds of practical restrictions which are either site specific or have to do with the amount of compromises the architect and/or building owner is willing to accept. Anyway, even taking into account those restrictions, excellent data have been achieved with several *UNI-SOLAR*®-PV-systems. Table III summarises the results of *UNI-SOLAR*®-PV-systems in several western European locations.

Table III – Measured AC-yields of various *UNI-SOLAR*®-PV-systems in the Netherlands, Switzerland and the UK. Data courtesy of Ecofys (NL), Glattwerk (CH), and Solar Century (UK).

| Location | Product | Total power (kWp) | Monitoring period | AC-yield (kWh/ kWp/y) |
|---|---|---|---|---|
| Eindhoven, NL | SSR-128/ SSR-64 | 3.456 | 11/98-11/99 | 863 |
| Dübendorf, CH | US-64 | 6.912 | 1/99-1/00 | 916 |
| | | | 1/00-1/01 | 898 |
| Richmond, UK | SHR-17 | 1.088 | 3/99-4/00 | 827 |

The system in Eindhoven in the Netherlands consists of a standing seam metal roof on a private house in which *UNI-SOLAR*® PV-Laminates of 128 Wp and 64 Wp are integrated. The roof has an inclination of 15° and is oriented towards the southwest (215° with respect to north). A chimney and a few trees give some shadowing, especially during winter months. Ecofys, that has monitored the system over more than a year [3], has calculated that the orientation of the system gives rise to 7 % less insolation than the optimal equivalent. The system has been grid-connected in June 1998. The 64 Wp panels have been series connected in pairs so as to form 128 Wp units as well (in total there are 27 units of 128 Wp). Each such unit has an NKF-OK4 inverter of 100 Wp. Unfortunately, these inverters were under-dimensioned and several of them switched off when a high DC-current from the PV-panel came in (at high insolation levels). After switching off, they did not switch on again so that substantial energy yield from the modules has been lost. Therefore, the inverters have been replaced by new ones on Feb. 02, 1999. Fortunately, some individually monitored 128 Wp panels had inverters, which have remained intact throughout the testing period and therefore, it is possible to make a correction on the recorded AC-energy yield. Without such a correction, the system has generated 803 kWh/kWp over the one year period between November 1998 and October 1999. With a correction for the defective inverters, the system achieves 863 kWh/kWp in the same one-year period. Remark that poly-c-Si systems in resp. Amersfoort (School 'De Border') and Utrecht have generated 781 kWh/kWp resp. 744 kWh/kWp in that very same year. The Ecofys-study [3] concludes that this *UNI-SOLAR*® PV-system performs very well, remains stable and has generated about 10-15 % more energy than a standard-system based on c-Si, even though the in plane insolation is 7% lower than for the optimal orientation.

The system in Dübendorf (some 10 kms north of Zürich, Switzerland) consists of framed *UNI-SOLAR®* US-64 modules installed on the flat roof of Glattwerk AG, a local utility. Total rated power of the system is 6.912 kWp and the series-strings are connected to 2 ASP-inverters. The system was grid connected in November 1998 and data for both the calendar years 1999 and 2000 are available. Glattwerk AG has conducted the monitoring. In January 1999, the PV-system has been disconnected from the grid for about two weeks in order to do some finishing works on the cabling and the other two weeks of that month, the modules were covered with snow. The data have therefore been corrected (1999 only) with an energy output equal to the average between the December and February months in order to take the lost January month into account. Not only do the data for this system show fairly high energy yields, they also show that the modules remain stable over at least two years. Remark that the flat roof, on which this system is installed, receives quite some shadow from a neighbouring, much taller building. It is estimated that this shadowing accounts for minimum 10 % of lost insolation. In ideal conditions in Dübendorf, *UNI-SOLAR®* modules would generate at least 1000 kWh/kWp/year. Remark that the average annual energy yield of all systems in Switzerland over the years 1996, 1997 and 1998 was 858 kWh/kWp [4]. This is considerably less than for the Dübendorf-system.

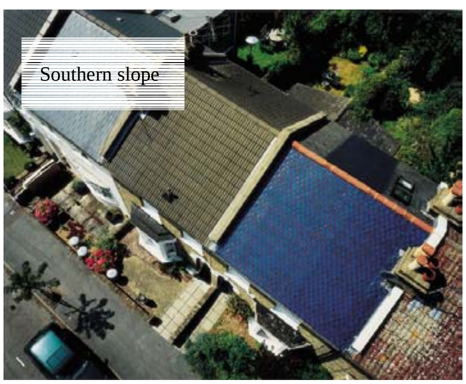


Fig. 4 A private house in Richmond (London) covered with *UNI-SOLAR®* PV shingles on the southern and northern slopes of the roof. Photo courtesy of Solar Century.

On a private house in a suburb of London (Richmond), a 1.632 kWp *UNI-SOLAR®* PV-shingle roof has been installed in March 1999. It is the first PV-installation in the UK to be completely made using electricity generating shingles. The PV-system consists of two separate parts: 64 SHR-17 PV-shingle units are installed on the southern face of the roof (total rated power 1.088 kWp), while 32 SHR-17 PV-shingle-units were placed for testing purposes on the northern slope (total rated power 0.544 kWp). The roof inclination is 40°. The PV-shingle units are connected in 6 series strings of 16 units, which are distributed over three SMA Sunnyboy SWR700 inverters. In the period March 1999 until March 2000, the southern slope system generated a total of 900 kWh, corresponding to a specific AC-yield of 827 kWh/kWp for the full year. This yield is very high for UK standards, especially if one considers the location of the installation: an urban environment close to a large airport (London-Heathrow) that causes serious air pollution. A typical c-Si PV-system under the same condition would generate in London no more than 700-720 kWh/kWp per year [5], some 15% less. It is interesting to note that the northern face installation also had a high yield: 528 kWh/kWp for the same period. This yield is still some 64% of the one of the southern face installation despite the fact that the insolation on that plane is more than 45% less than on the southern slope. This is a clear indication that *UNI-SOLAR®* PV-products perform well under non-ideal orientations.

## 5. CONCLUSIONS

The gathered data have shown that new generation multi-junction amorphous silicon solar modules, and in particular *UNI-SOLAR®* PV-products using Triple Junction solar cells, show good stability and excellent outdoor performance. These PV-modules actually perform better in real outdoor conditions than all competing c-Si and other thin film silicon products. The higher energy production of *UNI-SOLAR®* PV-products, up to 20% kWh per kWp purchased, can be understood by their excellent conversion efficiency at low light levels and their relatively insensitivity to ambient temperature.

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