

# A Comparison of the Performance of Different PV Module Types in High Ambient Temperatures.

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## *Abstract*

*The performances of five different types of photovoltaic modules have been measured during spring and summer in the temperate climate of Perth, Western Australia. The Perth summer averages over 7 peak sun hours (PSH) each day and has average sun-up temperatures between 25°C and 27°C. The types of modules examined in this study are: Crystalline silicon (c-Si), laser grooved buried contact (LGBC) c-Si, polycrystalline silicon (p-Si), triple junction amorphous silicon (3j, a-Si) and copper indium diselenide (CIS). Using a purpose built outdoor monitoring facility the energy production under actual operating conditions has been measured for each module. The monthly performance ratios (PRs) have been calculated for the different modules and a comparison is presented here. The I-V characteristics and maximum power at standard test conditions (STC) have been measured for each module prior to, and at regular intervals during, outdoor exposure. These values are compared to the manufacturers' values, and monitored over time for the modules operated in the field.*

## 1. INTRODUCTION

In designing any power generation system that incorporates photovoltaics (PV) there is a basic requirement to accurately estimate the output from the proposed PV array under operating conditions. PV modules are given a power rating at standard test conditions (STC) of 1000Wm<sup>-2</sup>, AM1.5 and a module temperature of 25°C, but these conditions do not represent what is typically experienced under outdoor operation. This paper summarises the monitored results of module operation during spring and summer in Perth, Western Australia, at reasonably elevated module temperatures for different PV technologies. During the daylight hours of the summer months the modules have an average back of panel temperature of around 35°C, but the maximum back of module temperatures are higher than 65°C.

It is well known that different PV technologies have different seasonal patterns of behaviour. These differences are due to the variations in spectral response, the different temperature coefficients of voltage and current and, in the case of amorphous silicon (a-Si) modules, the extra effects of photo-degradation and thermal annealing.

There is evidence that modules of differing technologies could be more suited to certain specific climates. Meike (Mieke, 1998), for example, has reported on the very different performance of two PV arrays installed in a hybrid power station in a remote community in northern Australia, 400km south of Darwin. One array consists of polycrystalline silicon (p-Si) modules and the other is made up of triple junction a-Si modules. His work has shown that in this tropical climate, with high ambient temperatures and high humidity during the wet season, the a-Si array produces up to 20% more energy than the p-Si array. Akmad et al. (Akhmad et al., 1997) have also indicated a-Si modules may be more suited to tropical climates.

In this work the performance of PV modules based on five different technologies has been compared. These are: Single crystal silicon (c-Si), p-Si, triple junction a-Si, copper indium diselenide (CIS) and the laser grooved buried contact (LGBC) c-Si modules.

The results show marked differences in the energy output of the different module types. The observed deterioration of the maximum power at STC of all the modules supports the results of similar work performed in both Switzerland by the Laboratory of Energy, Ecology and Economy (LEEE), at TISO (Chianese et al., 2000, LEEE, 2000), and in the Netherlands by the Netherlands Energy Research Foundation ECN, at Petten (Eikelboom & Jansen, 2000).

## **2. TESTING PROCEDURES**

The current-voltage and power-voltage characteristics at STC are measured on site at the Murdoch University Energy Research Institute (MUERI) with a SPIRE 460 Solar Simulator and using appropriate reference cells calibrated by the Japan Quality Assurance Organisation (JQA). This measurement system has a maximum error of +/- 3%. A single crystalline reference module is used with every set of STC measurements to monitor the consistency and stability of subsequent measurement sessions.

The ongoing outdoor tests being conducted at MUERI involve the measurement of the total energy generated by each module. By using individual maximum power point trackers (MPPTs) for each module a direct comparison can be made of the maximum possible energy production of different modules while they are subjected to identical meteorological and operating conditions. The maximum power point trackers were especially designed and built for this work and have undergone considerable testing to ensure they reliably track maximum power.

Most outdoor monitoring of individual PV modules uses regular I-V scans to characterise module performance, (Akhmad et al., 1997, Ikisawa et al., 2000, Rummel et al., 1998). By using MPPTs and recording the energy output continuously the modules are subjected to actual operating conditions. A survey of current literature has found only two other groups using continuously measured energy output of individual modules. These are LEEE in Switzerland and the Photovoltaics Research Group in the Department of Physics at the University of Port Elizabeth (UPE) in South Africa. LEEE are also using MPPTs to monitor and compare all the available energy from each module (Chianese et al., 2000) whereas UPE use a regulated voltage rather than an MPPT, and so simulate the performance of a battery charging system (Meyer & vanDyk, 2000, vanDyk et al., 1997)

The modules under test are mounted on a North facing rack that is tilted at 32° (the latitude of Perth). The parameters being monitored and recorded are: module output power, both the plane of array (POA) and the horizontal global irradiance, back of module temperature, ambient temperature and wind speed. The data acquisition system calculates module power from the module voltage and module current measurements. All these parameters are measured or calculated every second and then averaged over 10 minute intervals.

## **3. RESULTS**

### **3.1. STC Results**

Table 1 gives the manufacturer's rated  $W_p$  for each module purchased for this project, the manufacturer's initial guaranteed minimum  $W_p$  (IGM) or tolerance, and both the initial measured STC results and those measured after the given number of months of outdoor exposure under actual operating conditions. As the photovoltaic industry becomes more established module warranty periods have steadily increased. Some limited warranty periods are now up to 25 years. Mostly, modules are guaranteed to perform to a percentage of the initial guaranteed minimum power and occasionally to a percentage of the rated power. Table 2 provides a summary of the warranties for the modules used in this work and, if they have changed, shows the warranties currently available for these modules.

After the outdoor exposure the modules'  $W_p$  values are all still within the manufacturers' tolerances. All modules have experienced some losses in the maximum power measured. Figure 1 shows that the p-Si and c-Si experienced an initial drop in power in the first weeks outdoors, but have been relatively stable since; the CIS module and the new 3j, a-Si module have experienced a more sustained decrease in output.

**Table 1. STC results before and after outdoor exposure**

Module Make Model #	Cell Type	Wp, Rated (W)	Wp, IGM (W)	Wp (initial) (W)	Exposure (months)	Wp (after Exposure) (W)	% difference (from initial Wp)
Solarex SX-75U	p-Si	75	70	76.4	6	75.4	-1.4
BP BP275	c-Si	75	70	81.6	6	78.5	-3.8
Uni-Solar US-64	3j, a-Si	64	57.6	75.3	312 PSH* + 6 mths	58.6	-22.2
BP BP585	c-Si, LGBC	85	80	86.7	3	85.2	-1.7
Siemens ST40	CIS	40	36	40.1	9	34.6	-13.7
Photowatt PW750/70	p-Si	70	65	68.6	9	67.7	-1.3

\*Prior to being installed on the monitoring system, the Uni-Solar US-64 module underwent photo-degradation outdoors while being left in the open circuit condition. The module was tested regularly and included in the monitoring system once it had degraded to approx. 64Watts. This occurred after an outdoor exposure of 312 Peak Sun Hours.

**Table 2. Module Warranties**

Module Make Model #	Warranty applicable to modules in this study	Warranty currently offered for new modules (If different from previous column)
Solarex SX-75U	20 Year Limited Warranty Of 80% Power Output (IGM) 10 Year Limited Warranty Of 90% Power Output (IGM)	
BP BP275	20 Year Limited Warranty Of 80% Power Output (IGM) 10 Year Limited Warranty Of 90% Power Output (IGM)	
Uni-Solar US-64	20 Year Limited Warranty Of 80% Power Output (Rated)	
BP BP585	20 Year Limited Warranty Of 80% Power Output (IGM) 10 Year Limited Warranty Of 90% Power Output (IGM)	25 Year Limited Warranty Of 80% Power Output (IGM) 12 Year Limited Warranty Of 90% Power Output (IGM)
Siemens ST40	5 Year Limited Warranty Of 90% Power Output (IGM)	10 Year Limited Warranty Of 90% Power Output (IGM)
Photowatt PW750/70	25 Year Limited Warranty Of 80% Power Output (IGM)	

**Figure 1** also includes a module labelled UN-2. This is another US-64 3j, a-Si module that was purchased for another project in 1997 and was included in this work until all the new modules had been delivered. As would be expected from an older a-Si module, which has been in the field for some time, UN-2 is no longer experiencing any sharp photo-degradation. Instead it is showing a fairly stable maximum power rating with some underlying cycling of maximum power values as the photo-degradation and thermal annealing takes place. There is a large difference in maximum power for the two a-Si modules. These modules have different dates of manufacture, 1997 and 1999. They are also very different in appearance, the older module is a duller brown colour, and the newer one is quite reflective and blue. This colour difference could be responsible for differences in the output of the modules, but further tests, such as spectral response and reflection measurements, would be needed to confirm this.

As mentioned earlier, the groups at LEEE and at ECN have noted similar drops in STC maximum power after outdoor exposure for all module types. These include a 10.7% decrease in maximum power for their CIS ST40

module after six months outdoor exposure reported by LEEE (Chianese et al., 2000, LEEE, 2000), and an ECN report of a 9.9% drop in maximum power for a CIS module after 5 months exposure (Eikelboom & Jansen, 2000).

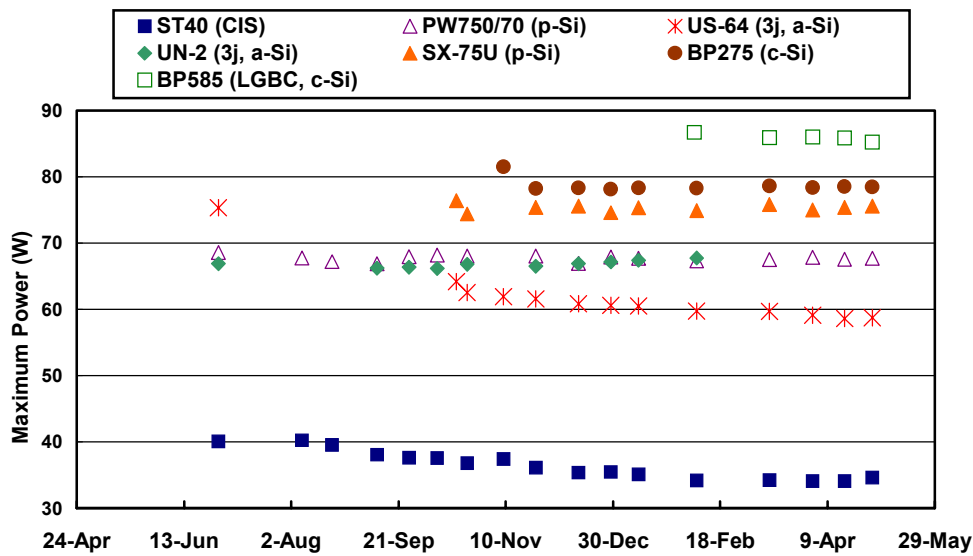


Figure 1. STC Maximum Power for different modules.

### 3.2. Outdoor Test Results

There are many ways to analyse the performance of PV modules. An increasingly common measure of actual energy production is the performance ratio (PR) (IEA, 2000), which enables the comparison of modules of different power ratings by normalising the energy produced under actual operating conditions to the maximum power of the module at STC and the incident solar radiation. Different qualities can be examined by using either the rated  $W_p$  or the measured  $W_p$ . The latter provides a direct comparison of the different technologies. The former enables an economic comparison of module brands and models, a guide to what may be expected from the different manufacturers. Most designers, installers and users of PV will not have the facilities to perform STC measurements, and will be particularly interested, therefore, in the performance with respect to the rated maximum power.

Looking at the long-term module efficiencies is another analysis method, either based on module area or aperture area. This is important when users are restricted by available space when installing a PV array. In most remote area applications in sparsely populated places, like Australia, this would not be an issue, but for roof mounted, building integrated PV in densely populated places, like Japan, this could be an important consideration.

For the analysis in this work, the monthly PR for each module has been examined. The total energy generated by the module under outdoor operating conditions has been measured and then both types of PR (Equation 1) have been calculated.

$$PR = \frac{E}{P_{MAX(STC)}} \bigg/ \frac{H}{G_{(STC)}} \tag{1}$$

- $E$  = Energy Produced (Watt.hours) in the given month
- $H$  = Total Incident radiation (Watt.hours/m<sup>2</sup>) in the given month
- $P_{MAX(STC)}$  = Maximum Power at STC measured each month, or the rated  $W_p$  (Watts)
- $G_{(STC)}$  = Irradiance at STC (Watts/m<sup>2</sup>)

Figure 2 and Figure 3 display the two types of PR values described. Figure 2 shows a decline in the PR based on

rated module output for all the new modules, with US-64 continuing to drop and the others appearing to level out. It is almost certain the continuing decline for US-64 is due to the photo-degradation and not a temperature or spectral effect, because, from August to October, the PR of US-64 drops, while the older, stable a-Si module, UN-2, has a constant PR.

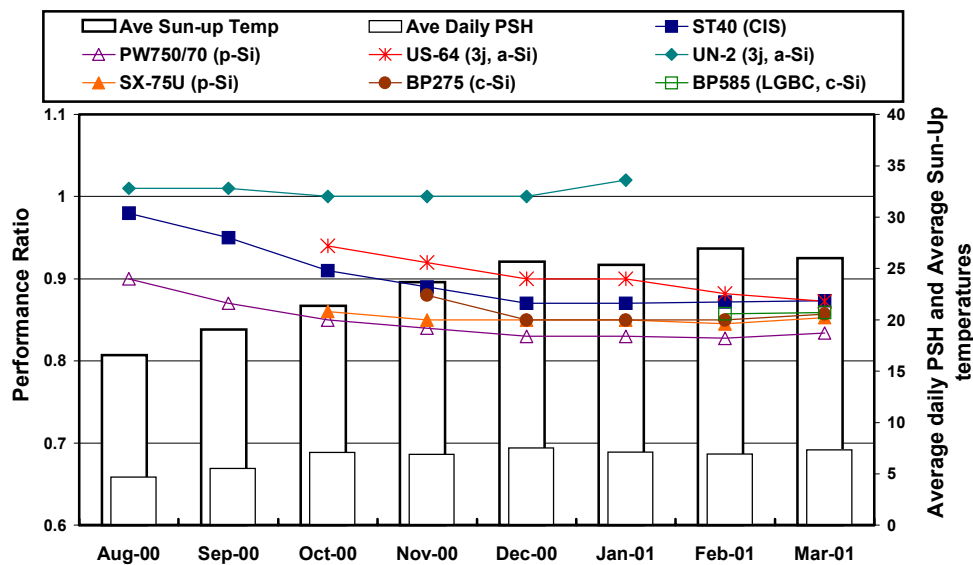


Figure 2. Monthly Performance Ratio, normalised to Rated Module Power.

Figure 3 uses the PR based on the measured module output at STC and provides a more direct comparison of the different behaviour due to material properties. The maximum powers used in the calculation of PR were taken from STC measurements, made as close to the middle of the given month as practicable. These measurements add the uncertainty of the simulator measurements to the PR calculations in this instance. The drop in PR seen in the PW750/70 plot between September and October is more than likely due to elevated temperatures. The other p-Si module SX-75U was not deployed until October. It shows a fairly constant PR from this time, as does the PW750/70. With only two months of data for the BP585, it is not possible to see any trends, except that the slight rise in PR between February and March could be due to the slightly lower average sun-up ambient temperatures in March.

In Figure 3 the c-Si BP275 module has the lowest PR. This is in contrast to its relative position in Figure 2 which was due to the maximum power of the module being unusually higher than the rated value. The two p-Si modules and the LGBC module have similar performance ratios that are higher than the c-Si, but the thin film devices all out-perform the c-Si and p-Si modules. During December and January the p-Si SX-75U is producing an average of 3.4% more energy and the other p-Si module, PW750/70, an average of 5.7% more energy than the c-Si BP275, while the stable 3j, a-Si module produces an average of 17.7% more energy than the c-Si module. During February and March the p-Si modules are still producing more energy than the c-Si module, with SX-75U generating 3.6%, and PW750/70 5.8%, more energy. The c-Si LGBC module, BP585, performs 3.6% better than BP275. The CIS module ST40, which by now has a fairly stable STC value, is producing 25% more energy than the c-Si module BP275. There is not such a definite delineation in the results given by LEE which may be due to the lower temperatures experienced in Switzerland (Chianese et al., 2000).

As the testing continues it will become clearer if the STC values of all the new modules have indeed stabilised, if they are continuing to slowly degrade, or if they are experiencing a cycling of maximum power like that experienced by a-Si modules.

In the summer months, in the temperate climate of Perth more energy is produced from the thin film modules than from the c-Si and p-Si modules using the PR based on either the rated or measured STC maximum power value.

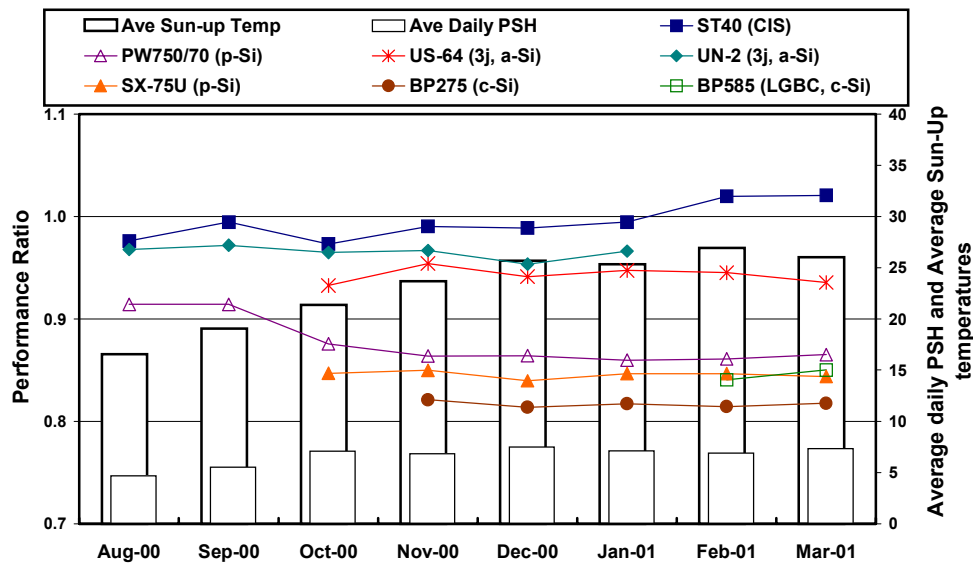


Figure 3. Monthly Performance Ratio, normalised to regularly measured STC peak power.

#### 4. CONCLUSION

These tests have shown that the STC values quoted by manufacturers for their PV modules do not necessarily match those observed in STC measurements. So far the measured maximum power values have remained within the values guaranteed by the manufacturers, despite a very steep decline in maximum power after outdoor exposure for some modules. This result has been aided by the relatively large tolerances manufacturers have specified.

An analysis of the performance ratio of six new and one old PV module has been conducted. The results show that there are more pronounced seasonal effects on the crystalline silicon technologies, due to elevated temperatures, than observed on the thin film modules. When looking at the material properties of the different technologies by examining the PR in figure 3, it has been found that the c-Si BP has the lowest performance ratio while being out-performed by the c-Si LGBC module. The CIS module has the highest PR calculated. The older UN-2 3j, a-Si module out-performs the newer US-64 module in both measured maximum power and PR, but, until US-64 has a stabilised maximum power, a proper comparison of the performance ratios of the two modules cannot be done.

By either measure of PR the results show that the thin film modules tested in this study produce more energy than the crystalline and the polycrystalline silicon modules tested in the Perth summer.

As the module STC maximum power values become more stable it will be possible to see more clearly the differences in performance of the different technologies, along with the seasonal effects of spectrum, temperature and light levels on module energy production.

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