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A comparison of the performance of different PV module types in temperate climates

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Abstract

The performances of five different types of photovoltaic modules have been measured for more than a year in the temperate climate of Perth, Western Australia. Perth averages over 5.4 peak sun hours (PSH) each day, from less than 3 in the winter months to over 8 at the height of summer. The average sun-up temperatures range between 16.5 °C and 28 °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 annual and 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 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.

Keywords: Performance ratio; Outdoor exposure tests; Maximum power point trackers; CIS; a-Si; p-Si

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 1000 W m^{-2}, 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 over a year in Perth, Western Australia, at reasonably elevated module temperatures for different PV technologies. For six months of the year the average back of module temperatures during the daylight hours are over 30 °C peaking at 36.5 °C in February. However 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 effect of photo-degradation and thermal annealing.

There is evidence that modules of differing technologies could be more suited to certain specific climates. 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, 400 km south of Darwin. One array consists of poly-crystalline 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

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p-Si array. 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 di-selenide (CIS) and the laser grooved buried contact (LGBC) c-Si modules.

The results show marked differences in the behaviour and 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 and Jansen, 2000).

2. Testing procedures

The current–voltage and power–voltage characteristics at STC were 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% (Nakano, 2001; Sutherland, 2000). The simulator is housed in a constant temperature room.

To confirm the stability of the STC test facility a single crystalline Sensor Technologies module, with a maximum power at STC of approximately 10 W, has been used as a reference throughout the testing period. This reference module is permanently housed in the constant temperature room and was measured with each of the simulator reference cells at the same time as all the other modules were being measured. An analysis of the results from the reference module measurements showed excellent stability in the STC testing conditions, with a standard deviation of less than 1% in all cases over the entire test period.

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 (mppt's) 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. Real-time tests using a calibrated HP E4350B Solar Array Simulator have determined that these mppts have a tracking efficiency of approximately 99%.

Most of the research groups performing outdoor monitoring of individual PV modules are using regular *I*–*V* scans to characterise module performance (Akhmad et al., 1997; Ikisawa et al., 2000; King et al., 2000; Rummel et al., 1998). By using mppt's 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 mppt's to monitor and compare all the available energy from each module (Chianese et al., 2000). The research group at UPE are monitoring the performance of different modules under the operating conditions of a battery charging system by operating the modules at a regulated voltage of 13 V rather than at mpp. The modules are connected to a load and battery bank via a voltage regulator with the load designed so the batteries always need charging (Meyer and van Dyk, 2000; van Dyk et al., 1997).

The modules under test in this study are mounted on a north facing rack 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 integrity of the data has been assured by regular calibration checks of all sensors and system components. The data acquisition system calculates module power from the module voltage and module current measurements that are made each second. 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 manufacturers' rated Wp for each module purchased for this project, the manufacturers' initial guaranteed minimum (IGM) Wp or tolerance, the initial Wp values measured prior to any outdoor exposure and the final Wp value measured at the end of the test period. Table 1 also presents the number of months of outdoor exposure experienced by each module, the percentage differences between the initial and final Wp measurements and the difference between the final Wp value and the rated output.

As the photovoltaics 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 per-

Table 1
STC results before and after outdoor exposure

Module make model #	Cell type	Wp, rated (W)	Wp, IGM (W)	Wp, initial (W)	Wp final (W)	Exposure (months)	Diff. initial to final (%)	Diff. final to rated (%)
Solarex SX-75	p–Si	75	70	76.4	75.3	16	−1.4	0.4
BP BP275	c–Si	75	70	81.6	78.7	16	−3.6	4.9
Uni-Solar US-64[a]	3j, a-Si	64	57.6	75.3	56.4	16 + 312 PSH[a]	−25.1	−11.9
BPBP585	c-Si, LGBC	85	80	86.7	86.1	13	−0.7	1.24
Siemens ST40	CIS	40	36	40.1	32.1	19	−20.0	−19.7
Photowatt PW750/70	p-Si	70	65	68.6	65.9	19	−3.9	−5.8

[a] 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 approximately 64 W. This occurred after an outdoor exposure of 312 peak sun hours.

centage 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.

The initial (prior to outdoor exposure) STC measurements of all the modules were within the IGM values given by the manufacturers. Of the crystalline silicon technologies (c-Si and p-Si) SX-75(p-Si) and BP585(LGBC, c-Si) have initial Wp values that are marginally above their ratings, 1.9% and 2.0%, respectively. BP275(c-Si) is 8.8% over its rated value. The p-Si module PW750/70 is approximately 2% below its rated value. Only one out of four of the crystalline technologies tested had a Wp value below its rated value.

As expected the a-Si module, US-64, has an initial measured un-degraded Wp value at STC that is nearly 18% over the rated 64 W. This is only a guide to the module's ultimate performance where an expected photo-degradation of 15% is given by the manufacturers (USSC, 1998).

Finally, ST40, the CIS module, has an initial Wp value which is essentially equal to its rated value. However, there are suggestions by LEEE, as well as Siemens Solar Industries and NREL, that simulator testing using pulsed light does not give reliable results when testing

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-75	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)	

copper indium diselenide (Cereghetti et al., 2001; Tarrant and Gay, 1999). As very similar long-term results were seen in this study, this is investigated in more detail later.

The results of these initial tests do not concur with those obtained by LEEE: in three studies combined they have reported that 26 out of 28 crystalline technology modules were below their rated values. The two modules above the rated values were less than 1.5% above and the overall average for the measured peak powers was 9.4% below rated value. Some modules had initial maximum power values below the guaranteed values given by the manufactures (Cereghetti et al., 2000; Cereghetti et al., 2001). van Dyk and Meyer (2000) have also reported initial STC values below rated values: in a report containing initial STC tests of seven crystalline technology modules, all but one is below its rated value with the overall average Wp measurement being 5.4% below the rated value. As the tests reported here are of a much smaller sample it is not unreasonable to conclude that this could be the reason for the difference.

Fig. 1 presents all the STC measurements over the course of this study. After the outdoor exposure the modules' Wp values are all still within the manufacturers' guaranteed values, due in part to the large tolerances given in the warranties. All modules have experienced some losses in the maximum power from the initial Wp values measured prior to outdoor exposure. The gap in STC data collection, between April and June, was due to a breakdown of the air-conditioner in the simulator room preventing the required temperature control for STC testing.

In the case of SX-75(p-Si), BP585(LGBC, c-Si) and PW750/70(p-Si) the drops in Wp value in the first three months of exposure are 1.5%, 1.7% and 0.8%, respectively, which are all within the error limits of the Spire solar simulator. However, BP275(c-Si) had a larger drop when first exposed, which amounted to 4% in the first 3 months. Fig. 1 shows that, while BP275(c-Si) did experience this initial drop in power, it has been very stable since, as have BP585(LGBC, c-Si) and SX-75(p-Si). PW750/50 was very stable in the first year, but has shown a slight decrease in the final 5 months. LEEE and ECN (Cereghetti et al., 2001; Eikelboom and Jansen, 2000) have noted similar drops in STC maximum power after initial outdoor exposure for crystalline technologies. LEEE have reported and investigated initial degrading of crystalline technologies and concluded this occurs during the first few hours of exposure and is in the region of 3% (Cereghetti et al., 2001).

The new a-Si module US-64 and the CIS module ST40 have both experienced more sustained and unexpectedly large decreases in Wp value.

As mentioned earlier there is a question about the reliability of testing CIS using a pulsed solar simulator, and, while ST40(CIS) shows a drop in Wp value at STC of 20% over the entire test period, this result was not reflected in its outdoor performance. Extrapolation of outdoor results to STC, using the method described by Strand et al. (Strand et al., 1996), demonstrated a drop of performance outdoors of only 8.5%, giving a final Wp value of 36.6 W, rather than the 32 W measured in the simulator. Tarrant and Gay reported greater stability of

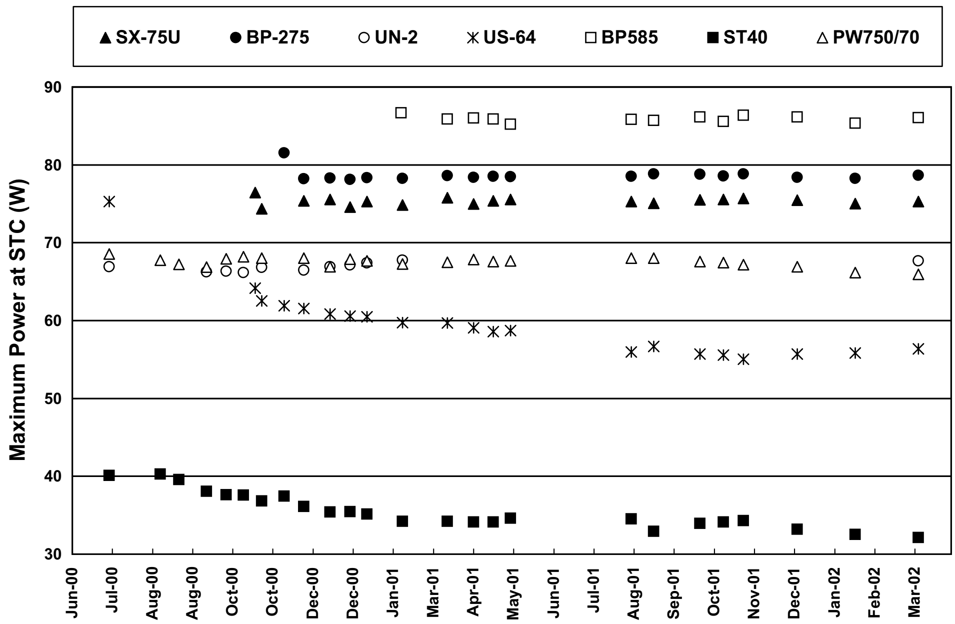

Fig. 1. Module maximum power at STC, measured using Spire 40 Solar Simulator.

CIS modules outdoors than when being tested using a pulsed solar simulator. They have reported on tests showing that both the voltage bias history and light bias history of the modules can cause transient effects, which, in turn, confound the results of measurements using pulsed solar simulators (Tarrant and Gay, 1999).

The a-Si module US-64 dropped over 25% at STC. At the end of the study the module had a maximum power at STC 12% below its rated value. It continued to degrade for more than a year, with the degradation process turning around (due to thermal annealing) in the warmer weather of December 2001. This prolonged degradation was unexpected. It is usual for light-induced degradation of a-Si modules to occur in the first weeks or months of outdoor exposure, after which the modules will become stable. This is confirmed by published results, for example (Akhmad et al., 1997; Lund et al., 2001). The manufactures also state that the degradation will occur in the initial 8–10 weeks of outdoor exposure (USSC, 1998).

Fig. 1 also includes a module labelled UN-2. This is another Uni-Solar US-64 triple junction a-Si module purchased in 1997 for an earlier separate project and included in this work until all the new modules had been delivered. As expected from an older a-Si module, which has been in the field for some time, UN-2(3j, a-Si) 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 very large difference in maximum power for the two a-Si modules. After more than four years of outdoor exposure UN-2 has a Wp value at STC of 67.8 W, 6% above Wp-rated, and as stated above, after 19 months US-64 is 12% below its rated value. These modules have different dates of manufacture, 1997 and 1999. They are also very different in appearance, the older module is a dull brown colour. The newer one is quite reflective and blue. This colour difference could be responsible for some differences in the output of the modules, but further tests, such as spectral response and reflection measurements would be needed to confirm this.

This result is not unique. LEEE have experienced and reported a similar result for two US-64(3j, a-Si) modules. The manufacturer requested the return of one of the modules to determine the cause of the low Wp value. The module was tested by the manufacturers and found to have a Wp value of 52.1 W, or 18.6% below its rated value. LEEE subsequently received another module from the manufacturers and found that, when stabilised, it produced 25% more energy than the earlier module (Cereghetti et al., 2000).

The company that produced the module has been asked for any additional information that may help to explain this unexpected result, but, to date, nothing has been received.

3.2. Outdoor test results

There are many ways to analyse the performance of PV modules. The system used in this study and an increasingly common measure of actual energy production is the performance ratio (PR) (IEA, 2000; IEC, 1998). It enables the comparison of modules of different power ratings, by normalising the energy produced under actual operating conditions to the maximum power at STC of the module and the incident solar radiation. Different qualities can be examined by using either the rated Wp value (Wp-rated) or the measured (at STC) Wp value (Wp-measured) as the normalising factor. The latter provides a direct comparison of 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. The general equation for PR is given in Eq. (1).

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 study, the annual and 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 [Eq. (1)] have been calculated

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

E energy produced (Wh) in the given time period
H total incident radiation ($\mathrm{Wh\,m^{-2}}$) in the given time period
$P_{\mathrm{MAX(STC)}}$ maximum power at STC measured during the time period, or the rated Wp (W)
$G_{\mathrm{(STC)}}$ irradiance at STC ($\mathrm{W\,m^{-2}}$)

3.2.1. Annual PR results

Fig. 2 presents the annual performance of the six modules under test. This includes both the PR, calculated using the rated maximum power for each module, and the PR calculated using the measured maximum

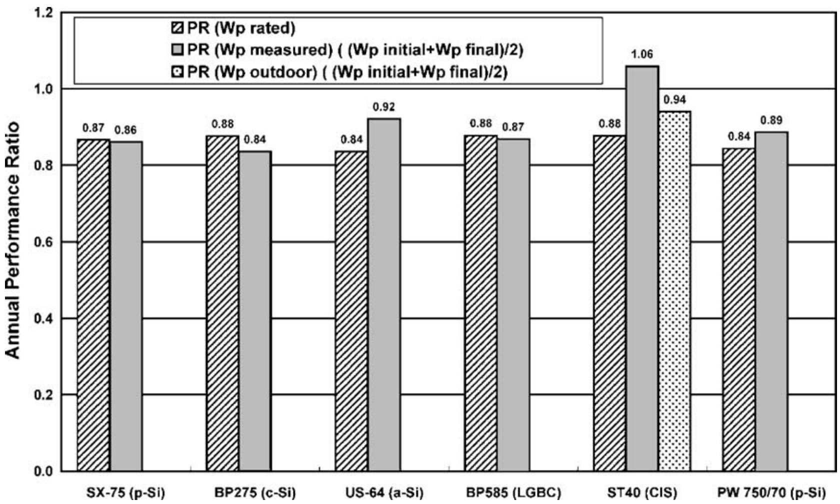

Fig. 2. Annual performance ratio for each module, based on both rated and measured Wp values. Taken from data for the year from March 2001 to February 2002.

power for each module. In the latter instance the measured value has been taken as the average of the Wp values measured in the solar simulator at the beginning and at the end of the test year (March 2001–February 2002).

The CIS module, ST40, result of 1.06 cannot be taken as reliable. This quantity has been calculated using the STC measurements and, as mentioned in the previous sections, there are known problems associated with large area pulsed solar simulator (lapss) measurements of CIS. Therefore a PR (Wp-outdoors) has been calculated using the appropriate outdoor Wp values (at close to STC) which were discussed earlier. The result is a PR of 0.94 and is included in Fig. 2.

Looking at the annual PR (Wp-rated) it is apparent that SX-75(p-Si), BP275(c-Si), BP585(LGBC, c-Si) and ST40(CIS) with values between 0.87 and 0.88 have performed better than US64(3j, a-Si) and PW750/70(p-Si) with values of 0.84. This lower value represents a production of 4.5% less energy, compared to the other four modules.

However, the technology comparison, PR (Wp-measured), shows ST40(CIS) (Wp-outdoors) as the best at 0.94, US64(3j, a-Si) next at 0.92, with the others being between 0.84 and 0.89.

Both SX-75(p-Si) and BP585(LGBC, c-Si) have very stable Wp values at STC; their STC values are the closest to their rated Wp values, so there is no appreciable difference between the two PR values.

BP275(c-Si) also has a stable measured Wp value. However, it is about 5% higher than rated value, which explains why the PR (Wp-rated) is higher than the PR (Wp-measured). It can be concluded that, as a technology, BP275(c-Si) produces approximately 5% less energy than SX-75(p-Si) and BP585(LGBC, c-Si) for the given site conditions.

PW750/70(p-Si) has a PR (Wp-measured) of 0.89, and like BP275(c-Si) the difference in the two PRs is due to the difference between Wp-measured and Wp-rated values. However, in this case the PW750/70(p-Si) module has an STC Wp value below its rated value. On a technology basis this result shows PW750/70(p-Si) performs better than the other technologies. However, PW750/70(p-Si) has not been as stable at STC as the three modules already discussed so a firm conclusion is not possible.

This is also true of US-64(3j, a-Si); the technology based PR (Wp-measured) clearly shows a much better performance than the others, but, with an STC drop of 5.6% over the 12 month period, it is difficult to draw any firm conclusions. A comparison on a shorter time base will provide more information.

3.2.2. Monthly PR results

To help determine seasonal trends in this study the monthly PR for each module has been examined. The total energy generated by the module under outdoor operating conditions has been measured then both types of PR have been calculated. In the case of the PR (Wp-measured), the Wp values used were those measured as close as possible to the middle of the month in question. As US-64(3j, a-Si) continued to degrade during the months in which no STC data was obtainable, Wp values were extrapolated from the available data to be used in the calculation of the PRs.

Fig. 3 presents the average daily POA peak sun hours and average daily ambient temperatures (sun-up) expe-

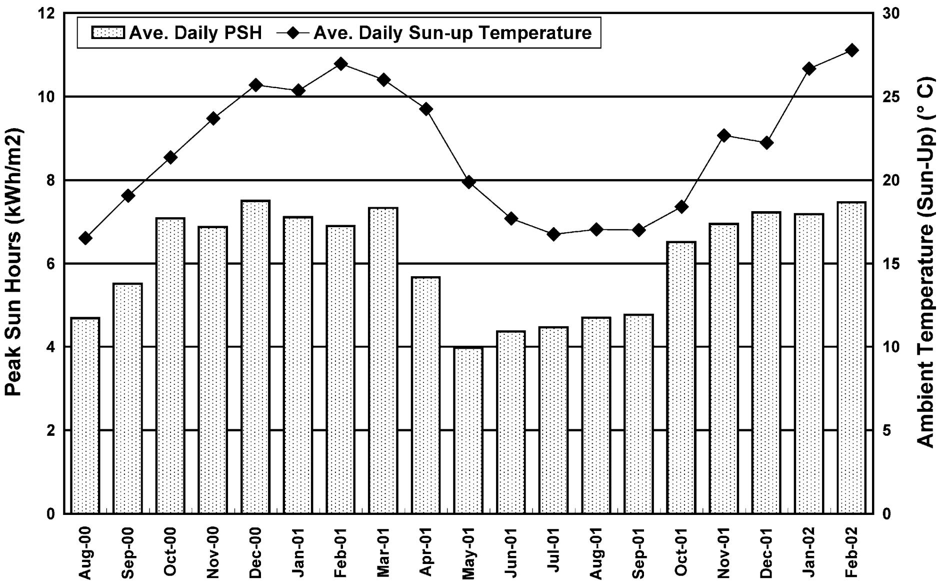

Fig. 3. The average daily plane of array peak sun hours (PSH) and average daily ambient sun-up temperatures measured on the MUERI monitoring system.

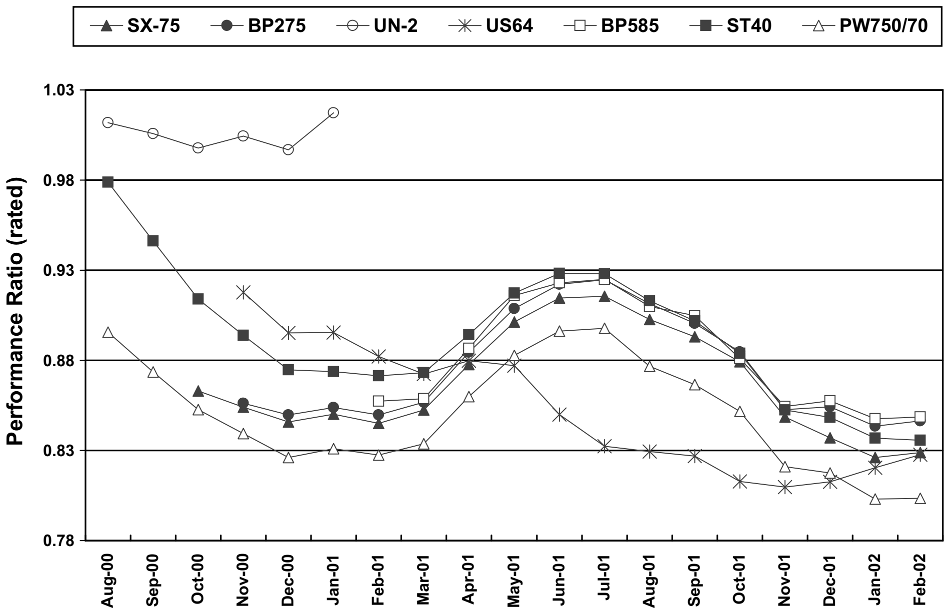

Fig. 4. Monthly performance ratio normalised to rated module power (Wp-rated).

rienced by the modules under test, while Figs. 4 and 5 display the two types of PR values described.

Fig. 4 shows the monthly PR based on the rated Wp values of the modules. The strong seasonal variation is apparent in the performance of the crystalline modules, as it is in the CIS module. The clear improvement in the cooler months is apparent, when ambient temperatures and hence cell temperatures are lower.

It is not possible to clearly see seasonal effects on US-64(3j, a-Si) as the module was not stable and continued to degrade as was previously discussed. This continued degradation tends to mask any other effects.

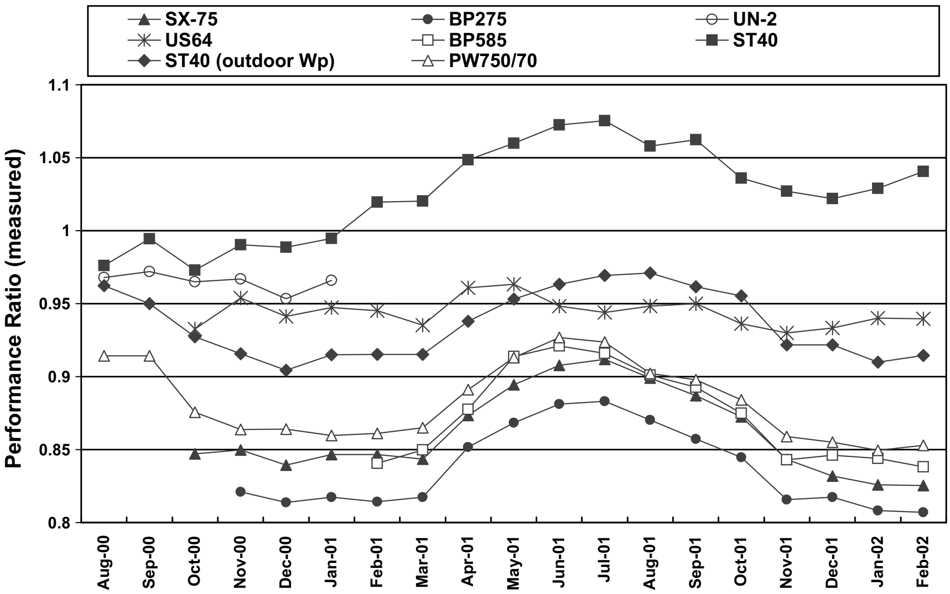

Fig. 5. Monthly performance ratio, normalised to regularly measured STC peak power (Wp-measured).

However, what can be seen is that UN-2(3j, a-Si) performs better than any other module in this comparison, including its a-Si counterpart US-64(3j, a-Si). One reason for this high PR is the higher than rated Wp value of the module. For the six months that UN-2(3j, a-Si) was on the system its PR has remained fairly constant, which is in contrast to the falling PR seen in US-64(3j, a-Si).

Fig. 4 shows that, when first installed, the CIS module ST40 performed well above its 0.88 annual average seen in the final year. The plot makes it clear that, while ST40(CIS) outperformed the crystalline silicon modules in the first summer, it ended up with a PR similar to BP275(c-Si), BP585(LGBC, c-Si) and SX-75(p-Si) by late 2001.

While PW750/70(p-Si) followed the same trends as the other crystalline based modules, it did have the lowest PR. Like the annual energy production, this can be explained by the fact that it has a lower Wp value than its rated value.

Fig. 5 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. Again the seasonal variation in performance of the crystalline technologies is apparent. As in the annual energy comparison an extra set of data points has been included for ST40(CIS). These have been calculated using the monthly outdoor Wp values.

It is immediately apparent, when examining Fig. 5 that all four crystalline technology modules have PRs lower than those of the thin film modules. BP275, a standard c-Si module, has the lowest PR of all the modules under test.

The other three crystalline silicon-based modules perform between two and six percent above BP275(c-Si), with PW750/70(p-Si) having the highest PR of all the crystalline modules.

UN-2(3j, a-Si) has a performance ratio about 18% higher than BP275(c–Si). US-64(3j, a-Si) has a PR that compares far more favourably with UN-2(3j, a-Si) than it did when the rated Wp was used to calculate the PR. Removing the effect of photo-degradation by using these measured values reveals that US-64(3j, a-Si)'s performance varies very little seasonally.

The PR for ST40(CIS), calculated with the solar simulator Wp values, is again an unreliable quantity. The PR calculated using the maximum power values measured outdoors is a better indicator of the technology's performance when compared to the other modules. It shows a seasonal variation, as do the crystalline modules, but not as pronounced, and it has a performance ratio very similar to US-64(3j, a-Si), with some seasonal crossing over in which ST40(CIS) is better in winter and worse in summer than the a-Si module; this could be attributed to its higher temperature coefficient.

As a counter point to PRs, the values of monthly efficiency have been calculated [Eq. (2)] as the ratio of total energy output by the module to the total solar energy incident on the module and presented in Fig. 6.

$$\eta_m = \frac{E_m}{H_m * A} \tag{2}$$

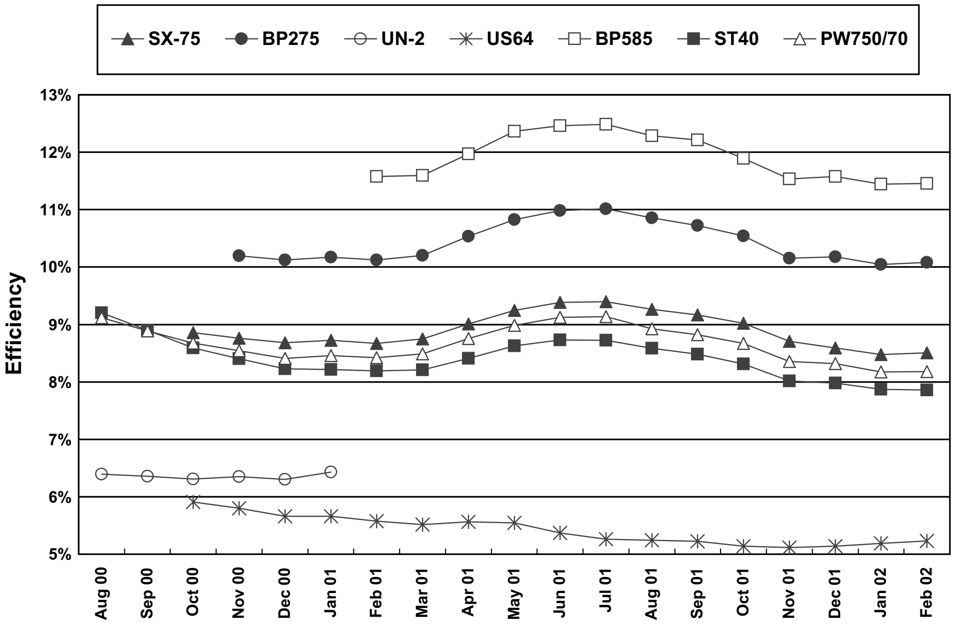

Fig. 6. Monthly module efficiency, based on total module area.

η_m	monthly module efficiency
E_m	total energy produced (Wh) in the given month
H_m	total incident radiation (Wh m^{-2}) in the given month
A	module area (m^2)

When space is a consideration this is a useful comparison. The superior module in this analysis is the LGBC c-Si module BP585, with efficiency values between 11.5% and 12.5%. Next is the c-Si module BP275, with values between 10% and 11%. The two p-Si and the CIS modules have midrange efficiencies between 8% and 9.5% and the lowest efficiencies are seen in the a-Si modules; UN-2 is better than US-64(3j, a-Si), but their efficiencies are less than or equal to half that of BP585(LGBC, c-Si).

4. Conclusions

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 large tolerances some manufacturers have specified.

The conclusions that can be drawn from the energy generation results are that, if all the modules had been stable and had Wp values equal to their ratings, the thin film modules would generate the most energy at this site. The triple junction a-Si modules produce over 15% more energy than BP275(c-Si) does in summer, and around 8% more in winter. The CIS module consistently produces between 9% and 13% more energy than BP275(c-Si).

However, not all modules were stable or had Wp values equal to their rated values. Despite being within the tolerances set down by the manufacturers some of the modules are far from their rated Wp values, and as noted, when looking at their performance based on their rated values, there is little to separate the crystalline and CIS modules from each other. The two a-Si modules are so different from each other that, based on these results, it is not possible to make any prediction of what could be expected from that type of module.

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