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Research Article

Experimental Study of the Degradation of Silicon Photovoltaic Devices under Ultraviolet Radiation Exposure

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This paper presents an analysis of the effects of ultraviolet (UV) exposure on amorphous silicon (a-Si), bare crystalline silicon (c-Si), and epoxy resin encapsulated c-Si devices. The long-term reliability of photovoltaic (PV) modules is crucial in ensuring the viability of PV as a successful source of energy. Accelerated UV ageing methods are required to quickly evaluate the UV durability of module materials. A UV exposure unit was designed and constructed and provided an average of 45.7 W/m^2 of UV irradiance over the exposure area with a nonuniformity of 14.9%. The a-Si devices lost up to 44% of maximum power (P_{max}) at Standard Test Conditions over 500 hours of exposure to UV, with maximum losses of 11% in short-circuit current (I_{sc}), 11% in open-circuit voltage (V_{oc}), 23% in voltage at P_{max} (V_{mpp}), and 29% in current at P_{max} (I_{mpp}). The epoxy resin encapsulated samples lost up to 6.4% in P_{max}, 6% in I_{sc}, and 7% in I_{mpp} with the changes in V_{oc} and V_{mpp} being random. The bare cells showed relatively little degradation. UV radiation thus accelerates the degradation of a-Si devices, deteriorates polymeric encapsulates of modules, and possibly affects the antireflective coatings applied on solar cells.

1. Introduction

Photovoltaic (PV) modules are exposed to several environmental stress factors including ultraviolet (UV) radiation during their lifetimes. Polymeric materials are used to encapsulate the solar cells, thereby providing them with electrical insulation and protection against mechanical stress and environmental corrosion. However, the polymeric encapsulates are themselves degraded by terrestrial solar UV radiation in the form of UVA (320–400 nm) and UVB (280–320 nm) which are the main factors responsible for the ageing of exposed materials. Therefore, accurate prediction of module output power degradation over time is essential for an accurate estimate of the return on investment from a PV system. Ageing of amorphous silicon (a-Si) devices occur in two stages; there is a strong degradation in the beginning of the operating life due to the Staebler-Wronski effect and a smaller nearly steady degradation afterwards [1].

The IEC 61215 [2] standard for the crystalline silicon (c-Si) and the IEC 61646 [3] standard for the thin film terrestrial PV modules design qualification and type approval include a UV preconditioning test that requires subjecting the modules to 15 kWh/m^2 at $60 \pm 5^{\circ}$C in the wavelength ranges of 280–385 nm and 280–400 nm, respectively, with at least 5 kWh/m^2 in the UVB range for c-Si devices and 3–10% of the total energy in the UVB range for thin film devices. The UV irradiance over the test plane should not exceed 250 W/m^2 and should have a uniformity of ±15%. Manufacturers normally assign a lifetime of 20–30 years to their modules, but the current IEC UV tests which are widely accepted represent an equivalent outdoor exposure to the AM1.5 spectrum of only several months to about 1.5 years [4], depending on the geographical location. These tests are rather intended to provide a reasonable assurance of possible long-term reliable operation rather than forecasting the long-term stability of a PV module design. Therefore, accelerated UV degradation methods for mini modules are required as manufacturer's cannot allow a 20–30 years' UV dose to be achieved outdoors on full-sized modules, which will be time consuming and expensive as a qualification test. Moreover, commonly available mini modules are used in various applications such as solar lights, solar battery chargers, toys, and several other electronic devices. Limited studies have been performed on the long-term UV degradation of PV modules, but yet none has been found related to these widely used mini modules. Moreover, no study has been found related to the indoor degradation of mini modules. The research work presented in this paper has attempted to quantify the accelerated indoor degradation of PV mini modules.

Observed degradation in small commercially available PV modules as a function of total UV exposure less than 400 nm during accelerated indoor weathering was reported in [5]. Two different light sources were used; the first chamber had four 4 kW Xe arc lamps with 50 W/m^2 UV irradiance at T = 45–60°C module temperature and another chamber had a row of 48 fluorescent UVA 340 lamps with a total UV irradiance of 40 W/m^2 at T = 50–65°C. It was observed that all the c-Si module types suffered an initial degradation of about 2-3% in maximum power (P_{max}) at Standard Test Conditions (STC). With UVA 340, the m-Si module suffered a total loss of about 7% in P_{max} after a UV dose accumulation of about 1700 MJ/m^2, while the p-Si module had a degradation of about 8% in P_{max} with the same UV dose and visible browning was observed along the edges of the modules.

A UV radiation chamber was developed with light sources emitting solar-like radiation in the short wavelength and lower intensities in the long wavelength UV regions of the solar spectrum, with an irradiance up to 5 UV suns and uniformity within the tolerance specified by IEC 61215 [6]. It was shown graphically that enhancing T from 60°C to 90°C accelerates the tests by a factor of more than 10. A partial water cooling system was set up to maintain a reasonable temperature of the lamps which have lower UV output at higher temperatures. A total of 120 lamps, each rated 200 W, were used in a row and a maximum of 233 W/m^2 UVA and 12 W/m^2 UVB was achieved in the module test plane. As a test, 6 different commercially available c-Si modules based on EVA encapsulates were exposed in the chamber with 2 different condition sets. With dry UV at T = 90°C, a dose of 150 kWh/m^2 produced a maximum drop of up to about 4% in P_{max} for one of the modules. On the other hand, the changes in P_{max} seemed to be even stronger at 60% Relative Humidity (RH), T = 60°C, and UV radiation of 112 W/m^2.

The ageing behaviour of a-Si single-junction devices for a total of 1000 hours was investigated in varying light intensity, spectrum, and temperature conditions [1]. An environmental chamber with a set temperature of 25°C was divided into 4 separate compartments: 2 with halogen sources at different intensities, 1 with cool white LEDs, and 1 as dark reference. The samples in the dark showed no degradation; the samples exposed under the LED lights showed the largest degradation of about 30% in P_{max} at T = 36-37°C and those exposed under the halogen lights showed a degradation in P_{max} of 18–24% at T = 51–54°C and T = 61–63°C despite the fact that more light was emitted from the halogen sources than from the LEDs. The conclusion was that the quantity of light is not the only driving factor in the ageing process.

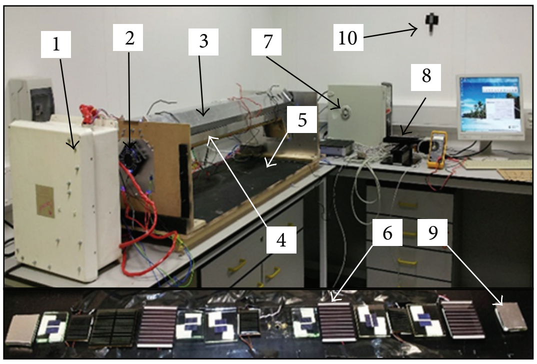
2. Methodology

2.1. UV Source Selection, Irradiance, and Spectrum Measurement. The IEC standards [2, 3] contain no detailed specification about the UV source spectrum and UV detector. Artificial UV sources with spectra comprising a large number of high energetic photons not present in terrestrial sunlight can cause unrealistic damage. Therefore the 40 W T12 UVA 351 linear fluorescent lamp [7] was selected as it simulates the UV portion of sunlight as filtered through the window glass and therefore provides better correlation to actual indoor exposure near a window. Moreover, the lamp has a very low contribution to the VIS-NIR region of the electromagnetic spectrum and thus does not cause excessive heating. A UV digital radiometer was used for fast measurements of irradiance during the design stage. Spectra and irradiance uniformity were measured using a VIS-NIR spectrometer. The lamp ageing was monitored throughout the experiment by using an AG32S UV photodiode-based amplifier which had previously been calibrated against the spectrometer.

2.2. UV Exposure Unit Design and Construction. A linear fluorescent lamp can be considered a cylindrical light source and the irradiance due to an infinitely long cylinder has been shown to be inversely proportional to distance from the source [8]. The exposure area was thus designed to be as close as possible to the lamps in order to achieve a suitably high irradiance. The latter was measured for different lamp arrangements involving 2–8 lamps and 4 lamps were found to provide the optimum UV irradiance. A reflector impacts on how much of the radiation output from a lamp reaches the area to be lit and also determines the light distribution pattern. Aluminium has a good spectral reflectivity (SR) in the UV range [9] and is a commonly used cheap material for reflectors in UV sources. The SR of pure aluminium sheet and some commonly available foils was measured using a UV-VIS spectrophotometer and the results led to aluminium wrapping foil being selected for the reflector inner lining. Several shapes of reflectors were tried and a trapezium shaped reflector was found to provide the highest irradiance and an acceptable uniformity.

The standard 40 W T12 linear fluorescent lamp is known have an optimum efficiency at a wall temperature about 38°C in open air [10]. However, this temperature was higher inside the reflector and when 4 lamps were operating close together. Cooling of the lamps was thus required and this led to the inclusion of air circulating fans in the test rig to achieve the best possible temperature distribution along the lengths of the lamps.

Following the design stage, the test rig was constructed and the lamp wall temperature was allowed to stabilise. The irradiance was measured at 90 points using the spectrometer sensor mounted on an X-Y plotter, which can control the position of the sensor underneath the reflector accurately. The uniformity over the exposure area was calculated as per [11].



1: power supply and safety circuit
2: cooler fan
3: aluminium reflector lined with kitchen foil
4: exposure bench
5: table
6: exposed PV device samples
7: data logger computer
8: *X*-*Y* plotter
9: exposed kitchen foil samples at both ends
10: relative humidity and room ambient temperature logger

Figure 1: Test rig setup.

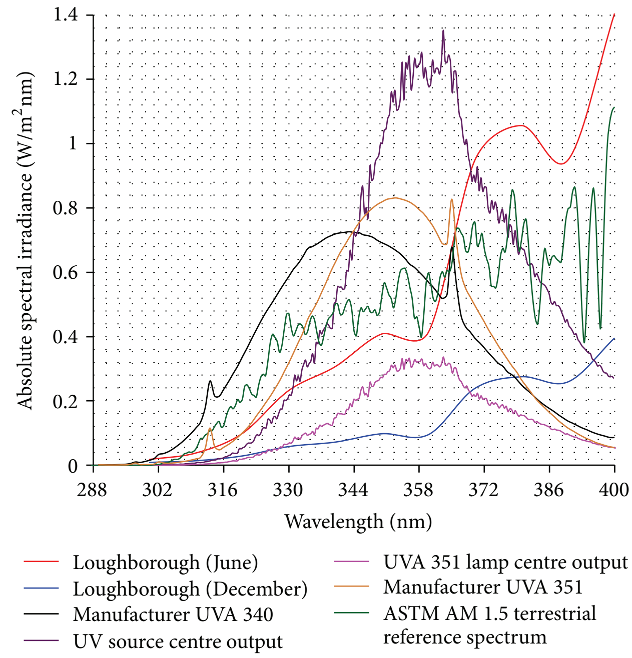


Figure 2: Spectrum measurements.

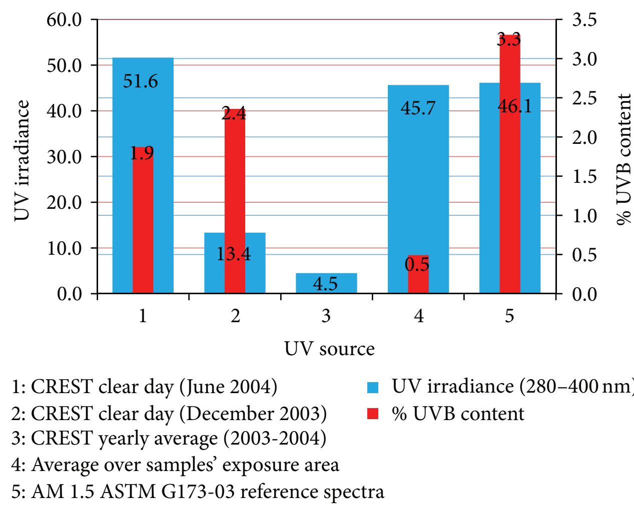


Figure 3: UV content comparison for different sources.

2.3. UV Exposure and Electrical Performance Monitoring. The irradiance map was used to determine a suitable exposure area with acceptable irradiance uniformity on the bench. Epoxy resin encapsulated c-Si (m-Si and p-Si), bare c-Si, and a-Si devices were used as samples for exposure during the experiment. The bare cell samples were covered with soda lime glass which is largely UV transmissive and TIO-coated glass which is partly UV transmissive. The temperatures of all the samples excluding the bare cells were recorded at 5-minute intervals by a CR800 data logger. The bare cells were too fragile to monitor their temperatures. The samples were successively shifted along the exposure area to average out effects of nonuniformity in irradiance and temperature. The STC electrical performance of each sample was measured initially and after successive exposure times using the PASAN solar simulator, whereby the temperatures of the samples were kept at $25 \pm 0.2^{\circ}$C. Each time 3 measurements were taken for each sample for repeatability.

3. Results and Discussion

3.1. Exposure Unit Measurements. Figure 1 shows the experimental setup. Two fans were used as extractor and blower fans to circulate air within the tubes and thus maintain a uniform lamp temperature.

Figure 2 shows the spectrum comparison for different UV sources. The measured UVA 351 lamp output spectrum is very similar to the manufacturer's measured spectrum. The slight difference depends on several conditions such as the room temperature and measurement position. When 4 lamps are used, the peak of the spectrum rises from about 0.33 W/m^2 nm to about 1.36 W/m^2 nm. The UVA 340 lamp is used to better simulate sunlight in the critical short-wave UV region and this correlates better to outdoor UV degradation. Figure 3 shows the total UV and UVB content of radiation from different sources. Comparing sources 4 and 3, it can be estimated that the constructed source provides an accelerating factor of 10 for the exposure in Loughborough. This takes into account the different weather conditions and day-night average for a typical year. As a result, it can roughly be said that a 20 years' UV dose of outdoor exposure in Loughborough can be achieved in only 2 years by the exposure unit.

Figure 4 shows the measured irradiance map over the bench. Over the whole area of 13 by 85 cm (positions 1-1 to 5–18), a uniformity of 34.7% was obtained. A middle portion of the bench having an area of 6.6 by 75 cm (positions 2-3 to

Table 1: Exposed samples.

Sample	Exposed samples	Control samples	Size (mm)
Epoxy resin encapsulated m-Si mini module	16, 17, and 18	15	39 × 35
Epoxy resin encapsulated p-Si mini module	14	0	57 × 65
a-Si single-junction mini module	20, 21, and 22	19	60 × 55
m-Si cells covered with soda lime glass	2, 3, and 7	13, 6	20 × 20
m-Si cells covered with TIO-coated glass	8, 11, and 12		20 × 20

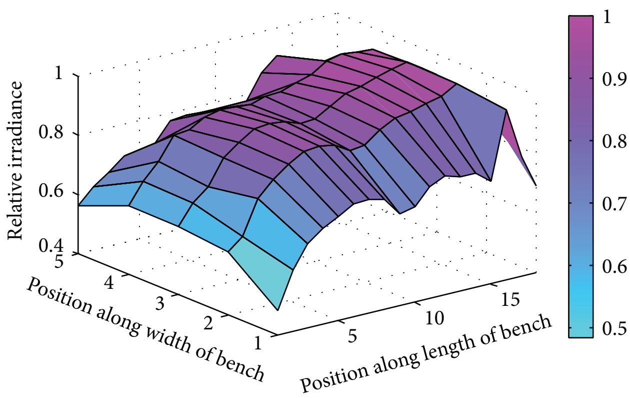


Figure 4: Measured irradiance uniformity.

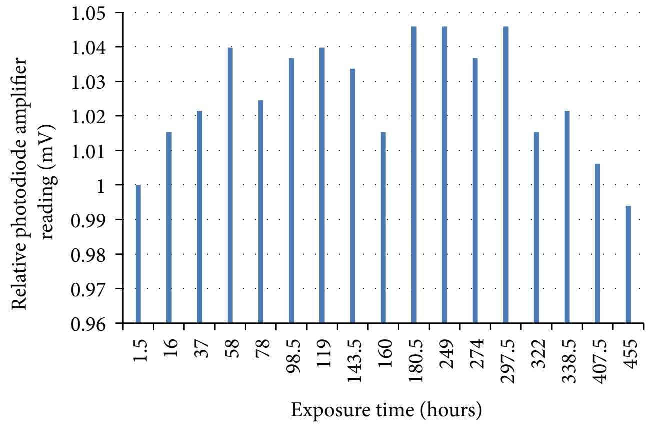


Figure 5: Lamp ageing monitoring.

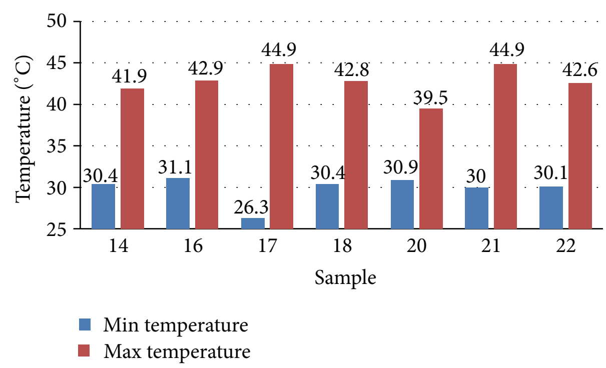


Figure 6: Temperature variation of samples.

4–17), with a uniformity of 14.9%, was selected for exposure of the available samples. Based on the dimensions of the samples, the maximum estimated uniformity was 7.6% over the p-Si and a-Si mini modules and 5.8% over the rest of the samples.

The lamp output was measured at a fixed position at different times and was found to remain relatively stable over the time period considered as shown in Figure 5. This suggests that the uniformity and irradiance levels did not vary much during the experiment.

3.2. Electrical Performance Measurements. The description of the mini modules and cells used in the experiment is provided in Table 1. Three samples in each category were exposed and there was one control sample for each category. The control sample was stored in a dark box. The back temperature variations of the samples during the total exposure period are provided in Figure 6. The simultaneous temperatures experienced by the samples were slightly different as this mainly depended on their positions along the bench, where temperature of air flowing could be different, and also on their thermal masses.

The maximum temperature difference between them at any instant did not exceed 10°C. However, all the samples experienced similar temperature variations as they were shifted along the bench during the exposure time period. This can be confirmed from the minimum and maximum temperatures experienced by the samples throughout the exposure period as depicted in Figure 6.

3.2.1. Degradation of a-Si Mini Modules. The ageing results of the a-Si devices are shown in Figures 7–12. Sample 21 suffered the largest degradation among the samples, of up to 44% loss in P_{max} over only 500 hours exposure. The P_{max} degradation rate is highest at the beginning and follows a nearly exponential trend. In comparison to [1], where 20%, 25%, and 28% loss in P_{max} occurred at 100, 250, and 500 hours exposure, respectively, under LED white light, in this analysis, a loss of 29%, 35%, and 45% has been measured at the same exposure times, respectively.

In 100-hour exposure under UVA 351 lamps, more degradation in P_{max} occurred than in 500-hour exposure in [1]. Ageing of a-Si is therefore strongly spectrum dependent as UV radiation accelerates the ageing compared to Halogen and LED sources with much lower UV content. After 500 hours, sample 21 had lost 11% of both its open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) while its maximum power point current (I_{mpp}) and maximum power point voltage (V_{mpp}) had degraded by 29 and 23%, respectively.

Despite the fact that the samples were shifted along the exposure area, the degradation trend is almost the same for the 3 samples and this confirms the low nonuniformity of irradiance. UV accelerates the degradation and therefore

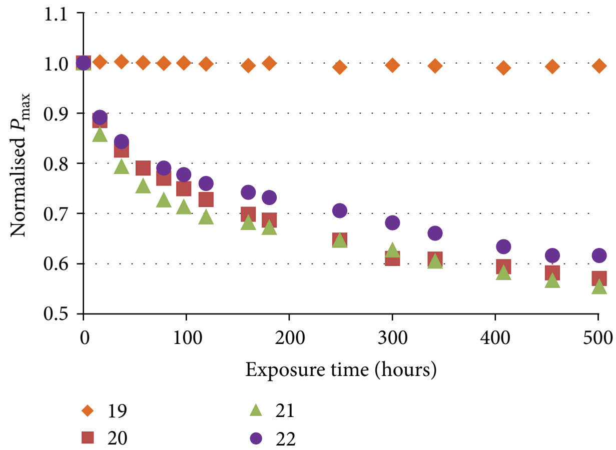


FIGURE 7: a-Si P_{max} degradation.

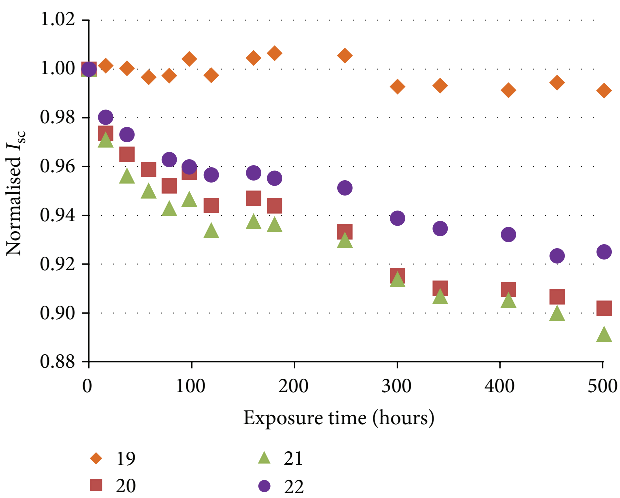


FIGURE 8: a-Si I_{sc} degradation.

large changes in irradiance over the exposure plane should have produced large deviations in P_{max} degradation trend. It should be noted however that all the results of degradation for all the samples involve uncertainties due to changes in the parameters of the control samples. Moreover, the differences in degradation rates of P_{max} of the samples can be explained by the temperature and irradiance differences experienced by the samples as they were shifted on the bench. The results reported in [1] showed similar differences in degradation rates, despite the fact that an air-conditioned chamber was used to maintain constant a temperature.

The colour changes in Figure 13 are an indicator that samples 20, 21, and 22 suffered degradation (deep maroon). The control sample 19 did not degrade (dark colour).

3.2.2. Degradation of Epoxy Resin Encapsulated m-Si and p-Si Mini Modules. The ageing results of the encapsulated c-Si devices are shown in Figures 14–19. A maximum degradation in P_{max} of 6.4% occurred for sample 16 at 500 hours. The control sample's parameters can be seen to have varied frequently from the unity value. However, it can also be observed

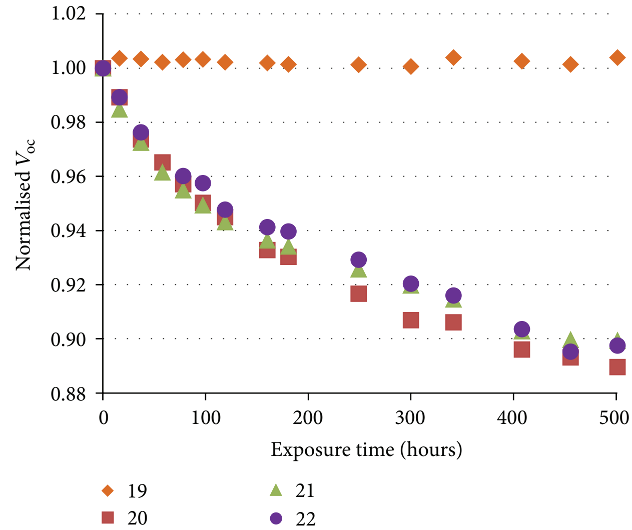


FIGURE 9: a-Si V_{oc} degradation.

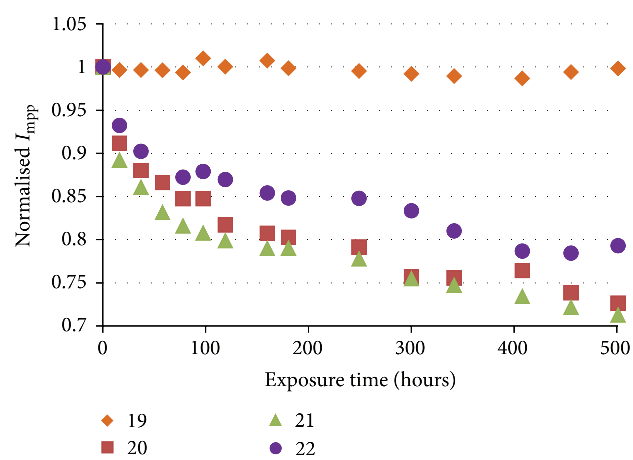


FIGURE 10: a-Si I_{mpp} degradation.

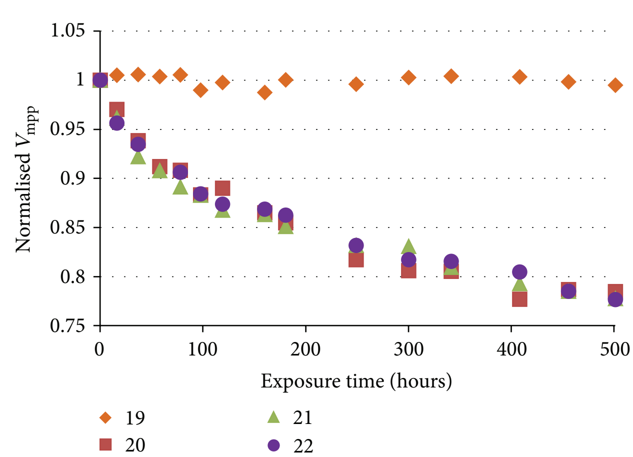


FIGURE 11: a-Si V_{mpp} degradation.

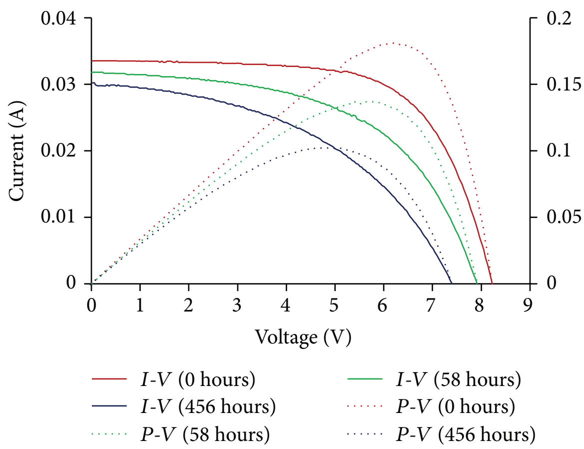


Figure 12: Sample 21 (a-Si) I-V and P-V curves.

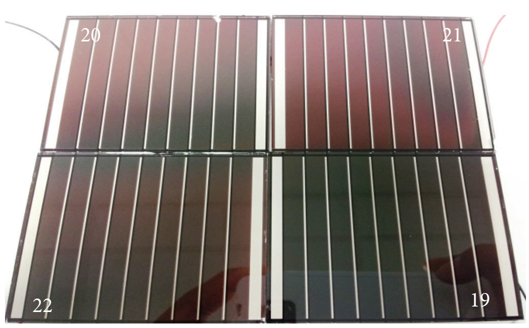


Figure 13: a-Si samples 19, 20, 21, and 22.

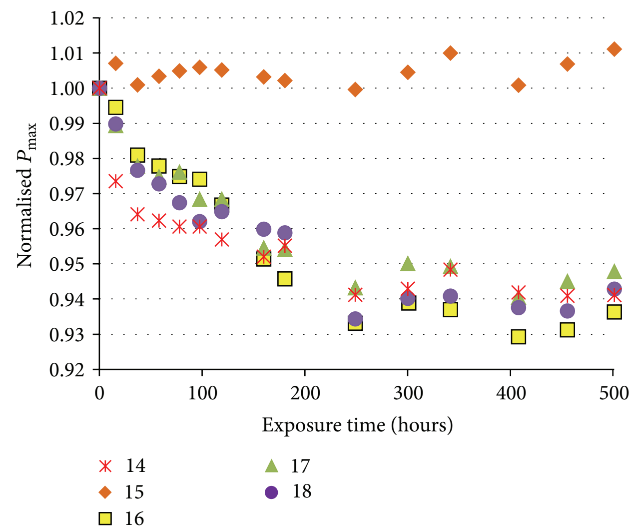


Figure 14: c-Si P_{max} degradation.

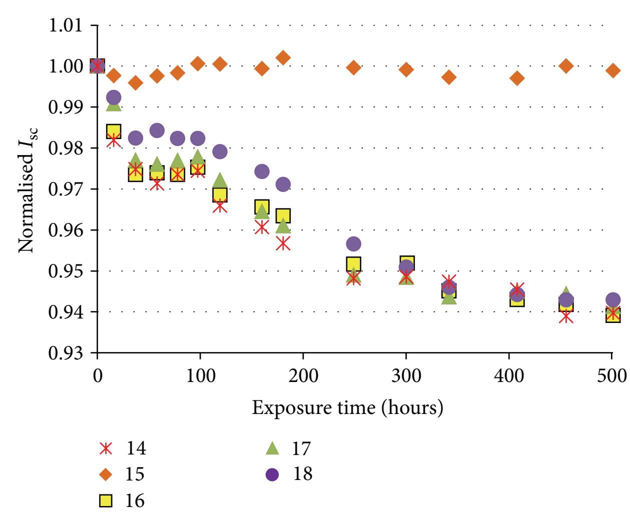


Figure 15: c-Si I_{sc} degradation.

that the parameters of the exposed samples followed nearly the same trend. One possibility of such a collective variation can be due to errors in measurements by the PASAN solar simulator. For example, if the control sample's P_{max} variation is considered with the errors, it can be estimated that the exposed samples should have shown a continuous loss in P_{max}.

I_{sc} and I_{mpp} of sample 16 have shown a relatively larger degradation of 6% and 7%, respectively, at 455 hours compared to 1.3% and 0.9% loss in V_{oc} and V_{mpp}, respectively, taking into account the deviation in parameters of control sample from their unity values. A general decreasing trend in V_{oc} can be observed whereas V_{mpp} varied randomly. The variations in P_{max} and I_{sc} were similar for all the exposed samples. Sample 14 (p-Si) showed similar degradation to that of the other exposed encapsulated samples.

The differences in degradation rates of the samples can be explained by the slight differences in the experienced temperatures and UV irradiance as they were shifted along the bench. Moreover, the data sheets of the samples did not mention the uniformity of the epoxy coating on the solar cells, but this can be an additional cause of the varying degradation rates.

Figure 20 shows a comparison between the appearance of degraded sample 16 and the control sample 15 where the effect of UV radiation on the colour of the module is clearly visible. The colour of the cells appears to have changed from dark blue to Oxford blue. In fact, the epoxy resin encapsulation has turned yellow and this is noticeable around the cells. One explanation about the loss of I_{sc} and I_{mpp} with exposure time is that the yellow encapsulate transmits lesser light to the cell than the clear encapsulate and the cell therefore generates lower photocurrent, causing lower output power.

3.2.3. Degradation of Bare m-Si Cells Covered with Soda Lime and TIO-Coated Glasses. Figure 21 shows the normalised P_{max} variation of the bare m-Si cells. The degradation in P_{max} can be attributed to the degradation in the antireflective coatings as reported in [12].

Control sample 6 was tightly enclosed in a plastic bag for the duration of the experiment while control sample 13 was left exposed to air in a dark box. Measurements were performed on sample 6 only at the beginning and at the end of the experiment, implying that the cell was not exposed to air,

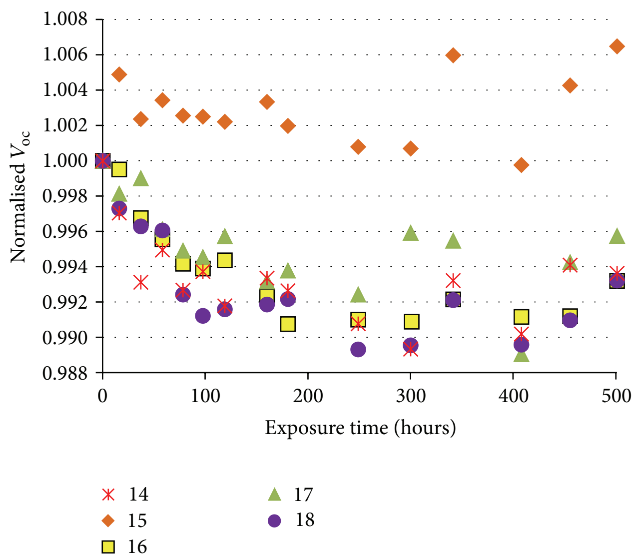


Figure 16: c-Si V_{oc} degradation.

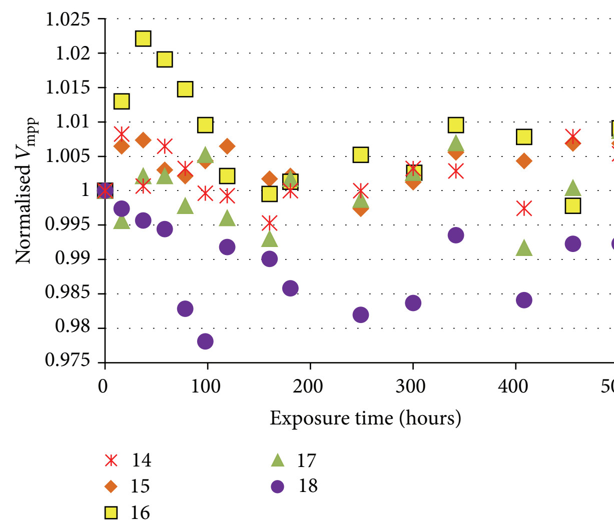


Figure 18: c-Si V_{mpp} degradation.

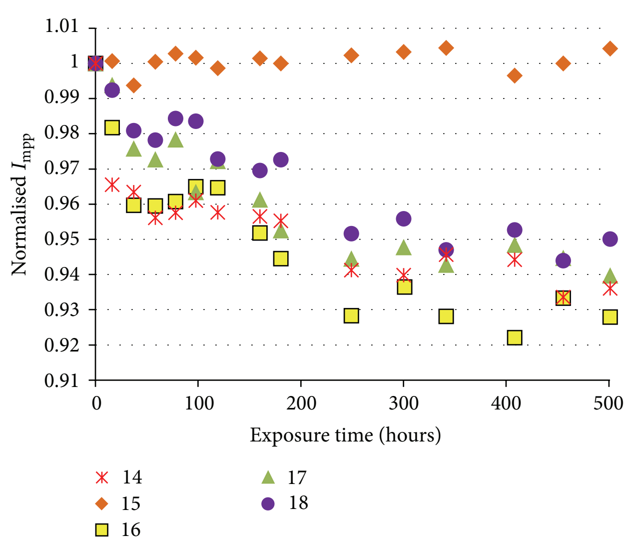


Figure 17: c-Si I_{mpp} degradation.

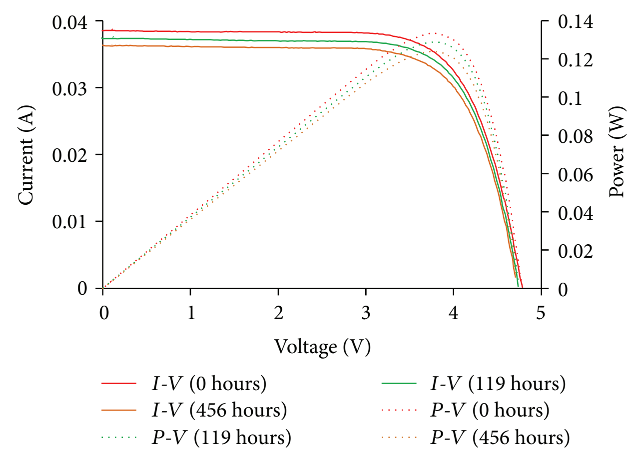


Figure 19: Sample 16 (c-Si) I-V and P-V curves.

whereas sample 13 was removed from the box for successive measurements, and was thus exposed to air. Sample 13 showed a level of degradation which is comparable to the exposed bare m-Si samples even though it was not exposed to UV irradiance. At this stage, no conclusion can be drawn about the degradation of sample 13 and this will be left as a future work in the field of degradation of bare silicon solar cells.

Figure 22 shows that the blue colour was brighter for sample 6 compared to all other samples at the end of the exposure period and this might explain the reason behind the degradation of the bare samples, with the exception of sample 6.

3.2.4. Other Measurements. Room temperature varied in the range of 19.5 to 27.5°C and RH in the range of 40.5% to 73% during the whole exposure period. As the samples underwent a full rotation, that is, the final samples arrangement being the same as the initial one, it is reasonable to assume that the dose achieved by all of them was 22.9 ± 14.9% kWh/m^2, the lower bound being when the sample sits at 37.6 W/m^2 for 500 hours and the upper bound when the sample sits at 50.8 W/m^2 for the same amount of time. Therefore, the total UV dose achieved was 1.25–1.69 times that was recommended by IEC 61215 and 61646 standards. Over 464-hour exposure, aluminium wrapping foil suffered an average loss of 4.6% in reflectivity over the UV range (280–400 nm) as shown in Figure 23.

4. Conclusions

This work has demonstrated the degradation of silicon PV devices upon exposure to UV radiation. The results show that UV radiation degrades polymeric encapsulates used in PV modules construction, thereby causing loss of output power over time. Moreover, it accelerates the initial degradation of

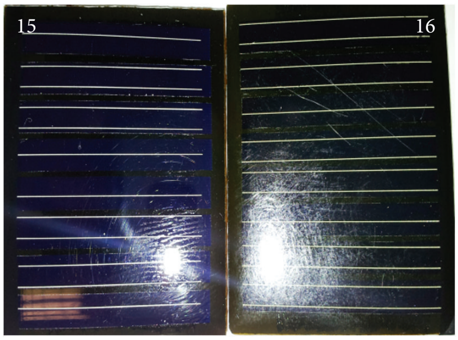


FIGURE 20: c-Si samples 15 and 16.

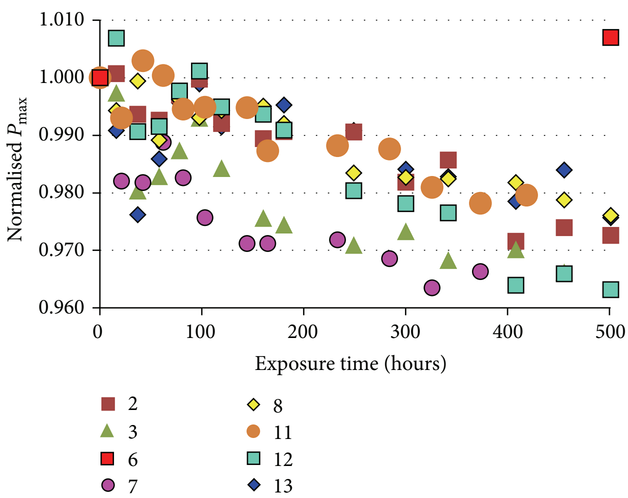


FIGURE 21: Bare m-Si P_{max} degradation.

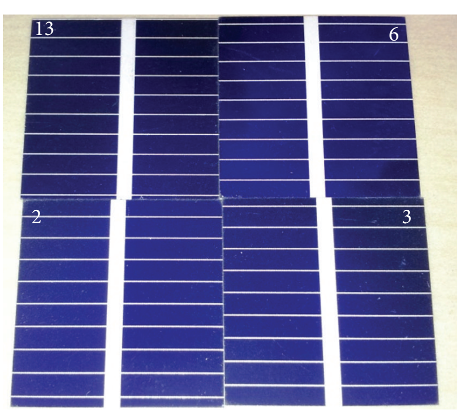


FIGURE 22: Bare m-Si samples 2, 3, 6, and 13.

the output power and causes a greater ageing in a-Si devices compared to exposure under broadband spectrum light with higher total irradiance but lower UV content. UV degradation involves a change in colour of materials. However, the effect of UV radiation, if any, on the bare crystalline silicon cells could not be determined with confidence in this experiment. Even if commonly available mini modules are used indoors, they are subjected to UV degradation. Epoxy resin

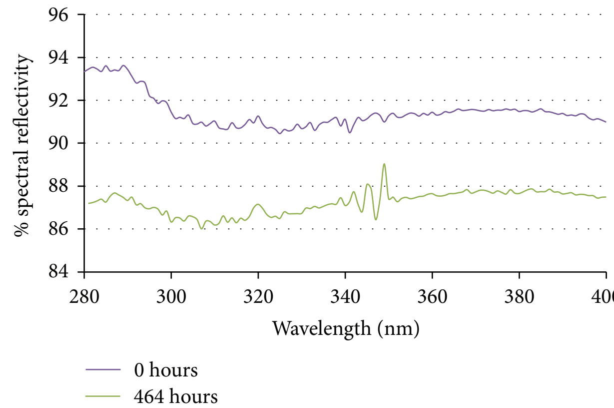


FIGURE 23: Aluminium foil % spectral reflectivity before and after exposure.

encapsulated PV mini modules are also widely used outdoors, and this research results can be safely extended to conclude that the outdoor degradation will be even worse, considering the fact that the UVA 340 lamps contain more UV than the UVA 351 lamps. This fact is very often ignored as the applications are relatively cheap. However, in the future, the importance of UV degradation of PV modules will grow, especially when the number of applications will increase.

Competing Interests

The authors declare that they have no competing interests.

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